LEONET Analysis --- A Procedure For Optimizing Ground Terminal Locations To Support Near Earth Missions

by

Sam Hsiaotung Liu

Submitted to the Department of Electrical Engineering and Computer Science on May 12, 1995, in partial fulfillment of the requirements for the degree of

Master of Science
and
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Abstract

This thesis presents an analysis procedure to optimally locate ground terminals to receive telemetry data for a specified set of 10 Low-Earth Orbiter (LEO) missions. LEO Network (LEONET) lost time percentage is measured for different combinations of ground terminal locations and network load distribution schemes during the analysis. A stochastic simulation tool, LEO4CAST, is used to generate the intermediate results from which the network lost time percentage is obtained. A heuristic analysis approach is taken for LEONET performance study. The interdependent relationship between the optimization of ground terminal locations and that of network load distribution schemes requires outer and inner iteration loops in the analysis. For the proposed LEONET, a set of optimal ground terminal locations is recommended for downloading the telemetry data of these 10 LEO missions.

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To my family and all my friends....

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Chapter 1 Introduction

1.1 Introduction

For the foreseeable future, the National Aeronautics and Space Administration (NASA) is shifting its attention to smaller and faster missions to study both Planet Earth and the solar system environment. More sophisticated remote-sensing Low-Earth Orbiter (LEO) missions are planned for the near future. With increasing LEO missions, there are increasing requests for telemetry downlink[1] support. Currently, the majority of the current LEO missions are supported by Tracking and Data Relay Satellite Systems (TDRSS) and White Sands Test Facility (WSTF) of Goddard Space Flight Center (GSFC). TDRSS is used for spacecraft tracking, command uplink, telemetry data, and spacecraft engineering data downlink. Some current LEO missions are supported by ground stations at Wallops[2]. A few current LEO missions are supported with direct links to ground stations by the 26m antenna subnet at Deep Space Network (DSN) of Jet Propulsion Laboratory (JPL) [1].

Due to LEO mission orbit characteristics and mission requirements, for many LEO missions, DSN is not the ideal ground station location to support their telemetry downlink. Nor is reception at Wallops ideal for many LEO mission due to Wallops high latitude location. The limited capacity of the DSN 26m antenna subnet and Wallops stations, as well as the high operational cost of TDRSS, cannot meet the increasing demands of LEO mission downlink support and the declining mission operation budgets. A LEO Network (LEONET) is proposed at JPL as an alternative to support LEO missions telemetry data downlink. The JPL LEO terminal Demonstration (LEO-D) team has successfully demonstrated the feasibility of using a low-cost and highly automated LEO-D receiver[3] with small aperture (3m) antenna to perform autonomous antenna pointing, telemetry data

[1] In general context, "downlink" refers to the physical links between satellites and ground stations. In this report, it refers more to the activity of downloading satellites' telemetry data to ground stations.
[2] GSFC is in Maryland, Wallops Station is in Virginia, and White Sands Station is in New Mexico.
[3] The LEO-D receiver is a non-prototype terminal built by Sea Space Corporation (San Diego, California) for technology demonstration purposes only.

acquisition, and data distribution[4]. LEONET consists of a number of LEO-D terminals, each of which is composed of a 3m antenna[5], an antenna controller, a receiver and bit synchronizer, and a SPARC workstation [2]. A pseudo instantaneous data distribution scheme, which delivers telemetry data to Principal Investigators (PIs) automatically via Integrated Services Digital Network (ISDN), saves data delivery time and cost. Besides the automated pointing, acquisition, and distribution systems, LEONET also has the potential for better coverage for LEO missions because ground terminal locations can be optimally selected to support a set of LEO missions. Consequently, better coverage results in higher percentage of scientific data return.

To determine the optimal ground station locations to support a set of LEO missions is not a trivial task. Their short orbital periods (~95min[6]) due to low apogee and perigee result in short view periods at one ground station. Different inclination angles and eccentricities introduce 2 more degrees of freedom and increase the complexity of ground station location optimization. Mission downlink requirements (number of downlink contacts per day and number of minutes per contact) can be exchanged with available satellite downlink data rates. Furthermore, there is a fraction of time when multiple satellites are in view at one ground station at the same time, resulting in mission-to-mission conflict[7]. All these factors, and there are many more, affect the successful satellite telemetry data downlink. Unfortunately, not all the parameters can be made to fit the selected ground station locations. Rather, the ground station locations have to be chosen to meet the parameters and requirements of these LEO missions.

This thesis project focuses on developing a procedure that deals with one of the complex issues of an optimal LEONET configuration. Specifically, this project seeks to obtain a procedure that optimally locates LEONET ground terminals to maximize data return for a

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[4] Currently, the LEO-D team is demonstrating the feasibility of command uplink utilizing the LEO-D type terminal.

[5] The antenna aperture size for future LEO-D terminals will probably be lager than the 3m used for the demonstration in order to maintain the necessary 3dB data link margin.

[6] "Min" is used as the unit for time in minutes. 6min is read as 6 minutes.

[7] Assuming there is one receiving terminal at one ground station, only one satellite can be supported at any given time at that ground station.

set of 10 specified typical LEO missions. It is the objective of this thesis to demonstrate this procedure as a generic approach for the LEONET ground terminal locations optimization. Hence, this procedure can be applied to not only these 10 LEO missions, but also any other specified set of one or more current and future LEO missions.

1.2 Motivation

This Section presents the comparisons made between currently used telemetry data acquisition and distribution systems and those of LEONET for supporting LEO missions. It covers the following four areas: resources, coverage, data delivery, and operational cost. The results reveal the incentives and motivations of utilizing LEONET instead of the DSN 26m subnet or TDRSS to support LEO mission telemetry downlink.

1.2.1 Resources

TDRSS consists of two operational satellites separated 130° in longitude in an equatorial geosynchronous orbit that is 35,800km away from Earth[8]. The principle ground support facility for TDRSS is WSTF. 1200km altitude is required for a spacecraft when passing over the Indian Ocean in order to obtain 100% TDRSS coverage because of the Earth's shadow seen by TDRSS. Figure 1 shows the simplified TDRSS orbit coverage [3].

Due to low altitudes of LEO missions, the slant paths from LEO satellites to LEONET ground stations are much shorter than that between LEO satellites and TDRSS. Because the required transmitted flux density is inversely proportional to the square of the maximum slant path, a direct link from spacecraft to Earth stations, such as that utilized in LEONET, is more desirable than a link from spacecraft to TDRSS and then to Earth stations.

With a 5° elevation mask, the maximum rise and set distance from a LEO spacecraft with 500km apogee to a ground station is 2078km. The maximum distance between this LEO

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[8] An additional satellite is in orbit (on top of the Indian Ocean) to replace either one of the satellites in the event of a failure.

satellite and TDRSS is about 37,124km. The difference in signal strength between the two spacecraft due to free space propagation loss[9] is about 25.04dB=20*log($\frac{37,124}{2078}$). Either TDRSS or LEO satellites need to be equipped with larger aperture antennas to make up for the high propagation loss [3].

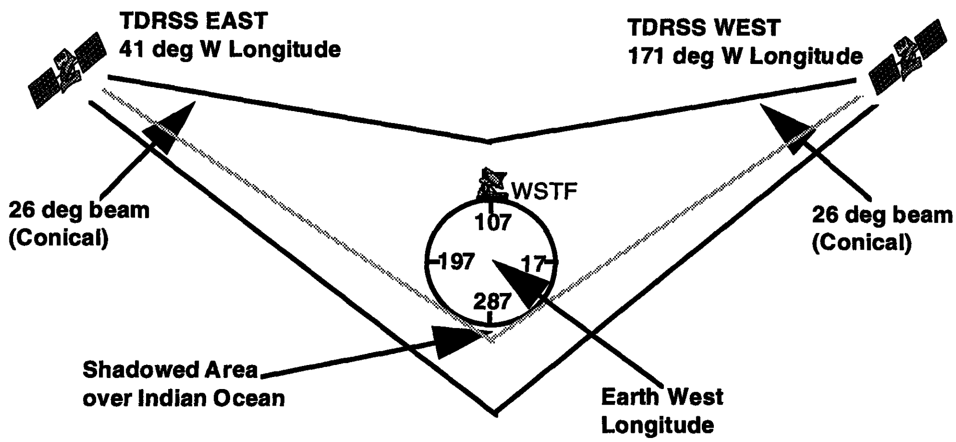

Figure 1: TDRSS configuration with Earth.

The DSN 26m antenna subnet is being utilized as the prime support from some current LEO missions[10] telemetry downlink. The Consultative Committee for Space Data Systems (CCSDS) requires at least a 12dB carrier margin[11] for telemetry signals [3]. The LEO-D receiver is recommended to have a 3dB or higher channel data margin[12] with 1.0×10^{-5} Bit Error Rate (BER). Most LEO satellites are designed to have 5 watt transmitter power and an omni directional antenna at S-Band (1.55~5.2GHz) downlink frequency [4]. The majority of the LEO missions' telemetry signals are strong enough to be received by ground terminals with 3m~5m small aperture antennas. A 26m antenna has an 18.8dB higher antenna gain than a 3m antenna[13]. The difference in antenna gain can be

[9] The free space loss is a function of frequency. The same downlink frequency is assumed for both cases.
[10] Even though the majority of the LEO missions are mainly supported by TDRSS, they may still require some levels of the DSN 26m antenna subnet support throughout their prime and extended mission phases. The DSN 26m subnet is also used for uplink for some LEO missions.
[11] The carrier margin is the difference between the total received carrier power and the total noise power inside the specified threshold loop bandwidth.
[12] The data margin is the difference between received signal E_b/N_o and required signal E_b/N_o.
[13] Assuming they have the same antenna efficiency, a 26m antenna has 20*log(26/3)=18.8dB more gain than a 3m antenna. The LEO-D antenna uses aluminum mesh structure and actually has less efficiency than a 26m antenna. Thus, the difference in antenna gain between a 26m and a 3m antenna is higher than 18.8dB.

directly applied to the received carrier power and data margin. Since a 3m~5m antenna is capable of receiving signals from LEO missions, using the 26m antenna to support LEO mission downlink is overkill. Although the 26m antenna subnet is required to support some LEO missions, utilizing LEONET will free up the 26m subnet and allow the 26m antennas to be arrayed together to support deep space missions such as Galileo.

1.2.2 Coverage

LEO missions utilize many low Earth orbits in a variety of inclination angles[14]. Each mission has its own optimal ground terminal locations for downlink. The optimal ground terminal locations yield maximum available contact time between the spacecraft and ground receivers. Consequently the ground stations for receiving LEO mission telemetry downlink need to be optimally located over the globe to maximize the performance of the network.

A JPL study [5][15] has shown that among the 90 approved NASA future LEO missions (a mission with multiple spacecraft is counted as multiple missions), 52 (or 57.8% of 90 LEO missions) are HIA missions, and 29 (or 32.2%) are LIA missions. The remaining 9 (or 16.7%) are MIA missions. The DSN consists of 3 sites which are located at Gold Stone, California (+35°, 117°), Canberra, Australia (-35°, 211°), and Madrid, Spain (+40°, 4°). Because of their ±35° and 40° latitudes, the 26m antenna subnet is optimal to support the 9 MIA missions but not the remaining 81 HIA and LIA missions.

1.2.3 Data Delivery

Currently, DSN and TDRSS receive telemetry data from spacecraft and forward them to GSFC[16] via the NASA Ground Communication System (NASCOM). Data is stored on

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[14] The orientation of the satellite's orbital plane is traditionally specified by the plane's inclination angle and the locations of the ascending node. The inclination angle is the angle between the orbital plane and the Earth's equatorial plane. 0° inclination angle orbit is also called equatorial orbit. 90° inclination angle orbit is also called polar orbit.

[15] "Future DSN support of Small Earth Orbiters: DSN long Range Plan," TDA/DSN No. 801-3, JPL Doc. No. D-10099, JPL, May 15, 1994.

[16] Data is also stored on tape as backups at DSN and other ground stations which utilize TDRSS.

tapes at GSFC and is usually Level-Zero (LZ) processed[17] within 24hrs. Figure 2 shows a current data delivery scheme for SAMPEX.

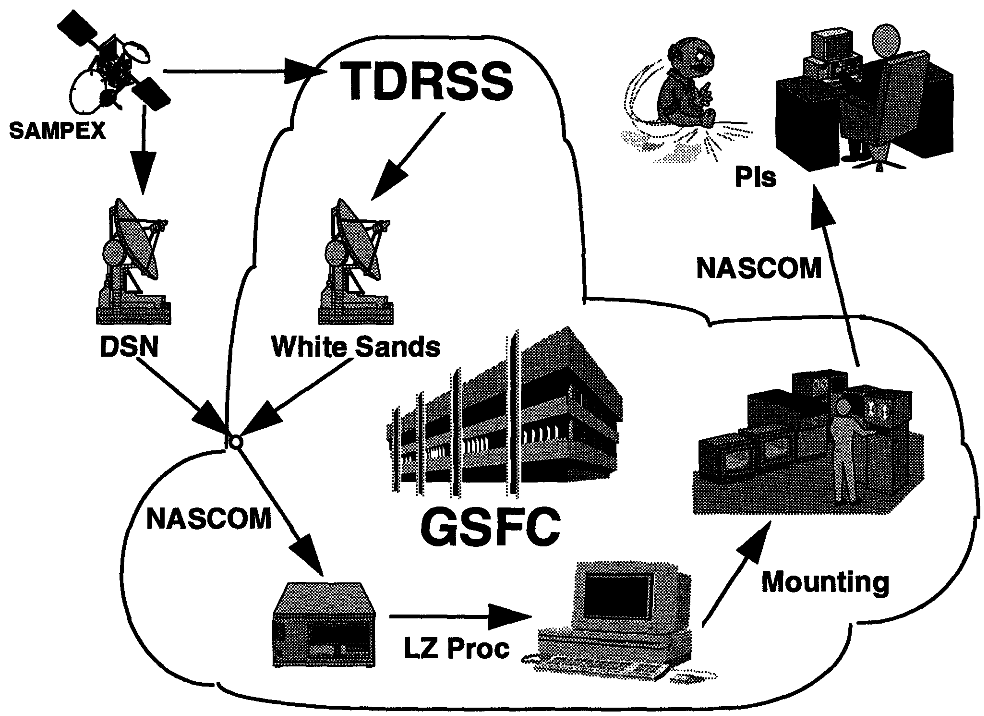

Figure 2: Current data distribution system.

Sometimes additional information, for example, weather and temperature data from other sources, might be time tagged to the original telemetry data during the process. GSFC stores LZ processed outputs on magnetic tapes and manually mounts them onto NASCOM, via which data is sent to PIs. It is inefficient in terms of both the time and the cost of delivering the data.

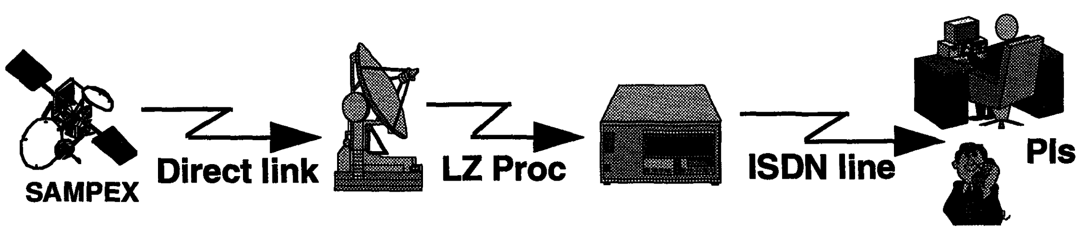

Figure 3: LEONET data distribution system.

LEONET, however, will have automated telemetry data acquisition and distribution systems. The LEO-D terminal receives telemetry data and automatically performs LZ

[17] The Level Zero processing differs for each mission.

processing[18] and the outputs are stored onto the hard disk in the SPARC workstation. The receiver then distributes the LZ processed data to PIs via ISDN lines. It saves both the time and the cost of data delivery. Figure 3 shows the LEONET data delivery scheme demonstrated by LEO-D terminal with LEO mission SAMPEX.

1.2.4 Operational Cost

TDRSS and DSN have very high operational costs. TDRSS receives LEO mission telemetry data, then downloads them to ground stations at WSTF for post processing and distribution. From the GSFC study [6][19] performed for LEO mission EUVE, the total operational cost to support EUVE in 1993 was $25.2M, of which $12.8M was spent on TDRSS, $1.6M was spent on space communication, and $10.8M was spent on space science. The study showed that when utilizing Direct To Ground (DTG) stations[20] without using TDRSS, such as a LEO-D terminal[21], EUVE operational cost would be reduced dramatically. The estimated total operational cost for 1996 using 2 DTG stations with 1 shift and 80% science data return rate is only $3.6M, which is only 14% of the 1993 EUVE operational cost. With 3 DTG stations, 2 shifts, and 95% science data return rate, the operational cost is $4.4M, or 17% of 1993's EUVE operational cost.

Furthermore, LEONET can be used to support more than one mission. Both the marginal and average operational cost for supporting an additional LEO mission (with the same required scientific data return rate) are expected to be less than the estimated operational cost for EUVE using DTG stations. The estimated maintenance for each LEO-D terminal is $40K/year. Utilities, on average, are $10~$15/day for electricity, and $100/day for all ISDN long distance phone call charges [2]. With LEONET, LEO mission operational

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[18] For SAMPEX, LZ processing is performed for every three downlink passes. SAMPEX has two passes each day that are approximately 12 hours apart.

[19] Bruegman, Otto and Douglas, Frank, "Study of low cost operations concepts for EUVE mission operations," Omitron Inc., February 22, 1994.

[20] The EUVE study assumes that each ground station costs $100K to purchase.

[21] A fully automated Turnkey LEO-D terminal built by Sea Space Corporation at San Diego, California costs around $200K, excluding $120K for the post processing software written in house at JPL and the cost of other hardware that are used for remote control purposes. The operational cost using LEO-D terminals for EUVE might be slightly higher than the one estimated in the EUVE study using the DTG stations. However, it is still only about 20~25% of 1993 operational cost.

cost can be dramatically reduced. The management complexity of DSN can also be simplified due to less required system reconfigurations for supporting LEO missions.

1.2.5 Summary

Tradeoffs can be made between spacecraft downlink data rate and the locations of ground terminals to improve the overall network performance. The non-real-time downlink is made possible by on-board storage devices. Larger solid state memory size and higher data rates are used to compensate for poor ground terminal visibility. Optimal ground terminal locations provide better coverage and hence smaller communication distances and smaller spacecraft on-board memory size. A JPL study [7] also shows that the advantages of lowered communication package mass, size, and power consumption, resulting from smaller communication distances at the expense of available on-board data storage, are amplified by the greater figure of merit (gain divided by noise temperature) of ground stations compared with space relay stations. Even though on board storage size of current in-flight missions cannot be modified, the optimal ground terminal locations can affect and improve future LEO mission system designs.

The higher data rate requires higher transmitted power on board for the spacecraft to maintain the required downlink data margin. This implies larger DC power requirement and thus a larger and heavier spacecraft. On the other hand, optimally located LEONET ground terminals provide LEO missions better coverage, which results in higher frequency and longer view periods, and consequently more available contact time. The longer mission contact time can utilized to exchange for lower spacecraft data rate (with fixed instrument readout rate). As a result, the weight and the cost of the spacecraft can be reduced. Furthermore, longer contact time simplifies the scheduling process and network management complexity for both spacecraft uplink and downlink.

In summary, the overall NASA cost of operating and supporting LEO missions are expected to be lower, using the DTG ground network (LEONET or DSN 26m subnet) rather than the space network (TDRSS). Furthermore, LEONET has numerous advantages over the DSN 26m subnet to support LEO missions, in terms of the ground terminal cost, operational cost, coverage, and data delivery scheme. LEONET provides a means of reducing NASA's LEO mission operating cost. It also provides means of meeting the increasing DSN 26m subnet support requests from non-LEO missions.

1.3 Background and Challenge

Currently, no program exists for deriving the optimal ground terminal locations that would support one or more LEO missions. Optimizing ground terminal locations requires a knowledge of the frequency and length of view periods for the set of LEO missions supported by LEONET. All readily available programs, such as POPS, PC-TRACK, and TERASCAN, use a deterministic approach to generate mission view periods. These programs cannot efficiently handle the uncertainties in mission orbit trajectories of both current and future LEO missions. Moreover, these deterministic simulations would need to be performed for a very long forecasting interval and would be extremely costly in terms of computing power and computation time.

A new program based on the stochastic simulation approach can handle the LEO mission orbit uncertainty more efficiently. As long as the simulation is intended for a long forecasting interval, the stochastic approach is appropriate and meaningful. LEO4CAST, developed in Section 311 at JPL, is one such program. The LEO4CAST simulation tool is capable of producing the expected view periods and the probabilities of mission-to-mission conflict. It is very useful for analyzing ground station performance for a given set of missions at a given ground terminal location. The raw data generated by LEO4CAST, such as ground terminal location quality factors, can be used to obtain LEONET performance metrics --- subnet and network lost time percentages[22].

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[22] The network lost time percentage is one of the important network performance metrics. It is the ratio of the amount of data lost to the amount of data collected by the spacecraft (that needed to be downloaded to ground stations). In this analysis, it only refers to the conflict between ground network availability and the requested support from the 10 LEO missions. The lost data due to spacecraft and ground network equipment failure are not considered. In this report, "subnet" refers to each individual ground station in LEONET, while "network" refers to all the ground stations in LEONET.

Because there is no closed-form solution to this problem of network performance optimization, a heuristic approach is taken for this analysis. The analysis procedure establishes two iteration loops to locate the optimal ground terminal locations and to define the optimal scheme for load distribution. These results would provide the least network lost time percentage with given network constraints. These constraints include the requirements for mission downlink as well as for network performance.

This analysis procedure focuses only on minimizing network lost time due to insufficient capacity of network ground terminals. The analysis does not consider lost time caused by other factors, such as expected equipment and ground network failure. Nor does this optimization analysis take other issues of practicality into consideration. Political factors, region spectrum interference, terrestrial data transmissions, and climate factors are all beyond the scope of this study.

The goal of this project is to develop this analysis procedure, utilizing LEO4CAST as its core engine, in order to determine the optimal LEONET ground terminal locations for any given LEO mission sets. The interdependent relationship between the optimization of ground terminal locations and that of load distribution schemes needs to be dealt with by the use of two nested iteration loops. The procedure is designed to minimize the necessary number of iterations during the analysis. Furthermore, the procedure must deal with the problem of the almost infinite number of possible combinations of potential ground terminal locations. It is impractical to go through each and every possible combination. The analysis procedure is intended to reduce the number of potential ground sites to a manageable but meaningful level.

1.4 Conclusion

The set of specified 10 missions under the study are EUVE, FAST, GRO, IRTS, SAC-B, SAMPEX, SASSE, SWAS, TOMS-EP, and XTE. Among them, EUVE, GRO, SAC-B, SASSE, and XTE are Low Inclination Angle (LIA, 0°~40°) missions; SWAS is a

Moderate Inclination Angle (MIA, 40°~70°) mission; and FAST, IRTS, SAMPEX, and TOMS-EP are High Inclination Angle (HIA, ≥70°) missions.

For the 4 ground terminal case, the simulation results show that the following 4 ground sites, Las Palmas, Canary Island, Spain (28°, 15°)[23], Maui, Hawaii (21°, 157°), Trinidad (10°, 62°), and Thule, Greenland (76°, 69°), are the optimal ground terminal locations. These 4 ground terminals are used to support these 10 LEO missions with the particular load distribution scheme[24], which results in a 1.51% network lost time percentage.

Chapter 2 briefly describes the selection, for use in this study, of the 10 typical LEO missions out of the 37 LEO mission pool. Chapter 3 introduces the core engine of the analysis procedure, LEO4CAST, and key network performance metrics used in the analysis. Chapter 4 presents the network performance analysis approach and the architecture of this analysis procedure. Chapter 5 describes some of the key analysis cases, shows key simulation and verification results, and ends with a recommendation for the selection of the ground terminal locations. Chapter 6 summarizes this LEONET analysis procedure and concludes with some important implications of this study. Chapter 7 provides the appendices, which include additional information on LEO4CAST and the 27 un-selected LEO missions.

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[23] All ground sites are characterized by their north latitude and west longitude.

[24] 2/3 of the IRTS mission load and 1/2 of the HIA+MIA (excluding IRTS) mission load are supported at Thule; 1/9 of the IRTS load, 1/6 of the HIA+MIA (excluding IRTS) mission load, and 1/3 of the LIA mission load (excluding SASSE) are applied to Las Palmas, Maui, and Trinidad; the SASSE load is supported at Trinidad.

Chapter 2 LEO Mission Set Selection

This section provides the reasoning and justification made for selecting the 10 LEO missions used in the LEONET optimization analysis.

Because of design and implementation complexity, when a new network is built, it always starts small and simple, then grows larger and becomes more complex. It is hardly ever the case that a complex network is entirely built in one step. For this reason, it is not necessary to analyze a large LEONET all at once. Furthermore, the more LEO missions to be supported by a network, the bigger the network is, and hence the more complicated the analyses are. One can easily lose insights when dealing with massive data manipulations.

The goal of this project is to establish a generic approach and construct a procedure for LEONET ground terminal location optimization. It is not desired to analyze a network with too many LEO missions and too many ground terminals. On the other hand, including too few missions in the study will not correctly reflect the dynamic behavior of the network, such as the tradeoffs between ground terminal capacity, mission-to-mission conflict, and load distribution schemes. It can be illustrated with the following analogy. It is similarly difficult to observe the dynamic behavior of gas particles if there are very few particles in a near vacuum chamber. For example, an equatorial LEO mission telemetry downlink can be supported by only one ground terminal located anywhere around the Earth's equator. In this case, there is no optimizations can be performed. As a compromise between the two extremes (too many and too few missions), 10 LEO missions have been selected for the study. Of course, there is no particular reason why there cannot be 9 or 11 missions.

Among the LEO missions that are and will be conducted by NASA by the year 2000 [8], 37 are chosen to form the LEO mission pool, from which the set of 10 LEO missions has been selected. The selected LEO mission set includes some of the current in-flight LEO missions, such as SAMPEX, EUVE, and GRO, as well as future LEO missions. The only two main criteria that have been used for the selection of these 10 LEO missions are:

- These 10 LEO missions have to be good representatives of the 37 LEO missions in the mission pool under the study, and hence good representatives of all current and future NASA LEO missions.
- For each mission, the required system G/T is less than that of a small (3m~8m) aperture receiver with 195K system operating temperature.

Detailed information on the 10 selected LEO missions are presented in Section 2.2, and those of the un-selected 27 LEO missions are listed in Appendices 7.3. These information include:

- Mission operational parameters
- Mission orbit parameters
- Mission telemetry downlink system parameters
- Mission data return requirement
- Resulted carrier and data margins

2.1 Mission Orbital & Telemetry Parameter Distribution

There are five main elements used to categorize the 37 LEO mission pool. They include mission orbit shape, apogee and perigee, inclination angle, requested contact time, and signal strength.

Orbit shape	Circular Orbit	Near Circular Orbit	High Elliptical Orbit
# of Missions	7	2	1

Table 1: 10 selected LEO mission orbit shape distribution.

Among the 37 LEO missions, ACME I and FAST are the only two Highly Elliptical Orbit (HEO) missions with 350km × 4200km and 250km × 5800km orbit respectively. ACME II, ASTRO-D, IRTS, NIMBUS-7, SAMPEX, and YOHKOH have near circular orbits. All other missions have circular orbits. The altitudes of all circular and near circular orbit missions vary from 200km to 1336km. However, the orbits of all near circular missions have rather small eccentricities and can be treated as circular orbits during the analysis.

Table 1 shows the orbit shape distribution for the 10 selected LEO missions and Figure 4 shows the 37 LEO mission orbit shape distribution.

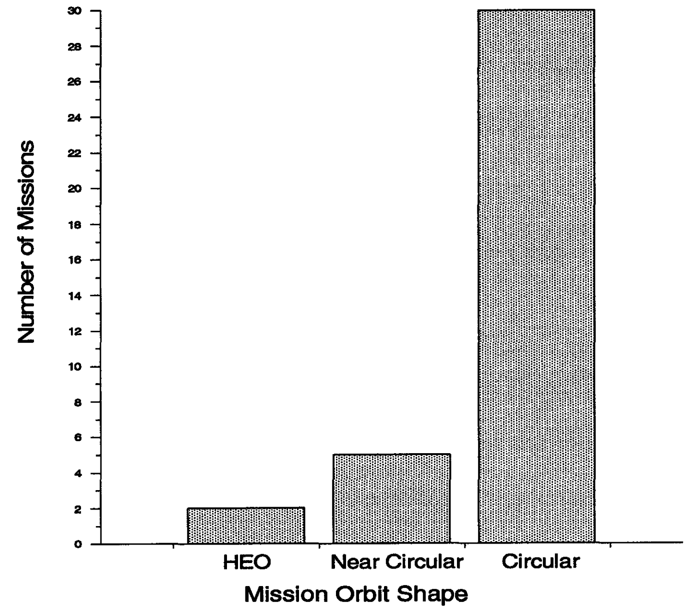

Figure 4: 37 LEO missions orbit shape distribution.

11 of the 37 LEO missions (just under 30% of 37 missions) have apogees between 400km to 600km. Only 4 out of 37 LEO missions have altitudes over 1000km (including ACME I and FAST). Figure 5 shows the 37 LEO mission apogee distribution.

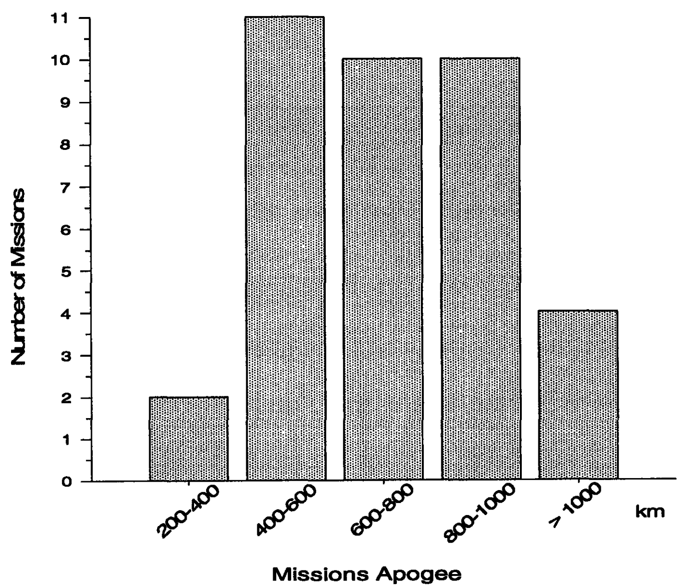

Figure 5: 37 LEO missions apogee distribution.

Mission apogees affect the view period duration at a ground terminal location. The lower the apogee, the shorter the average view periods. Mission apogee also has impact on the required spacecraft signal strength. At the same elevation angle, the higher the apogee, the longer the slant path range, and hence the weaker the signal strength, which results in smaller signal margin. Due to free space propagation loss, at 5° elevation angle, the short 1944km slant path of GRO and the long 7901km slant path of FAST have 12.18dB[25] difference in signal strength. Table 2 shows the mission apogee for the 10 selected LEO missions.

Mission Apogee	400-600 km	600-800 km	800-1000 km	>1000 km
# of Missions	5	3	1	1

Table 2: 10 selected LEO missions apogee distribution.

The 37 LEO missions can be categorized into three groups of LEO missions in terms of orbit inclination angle. 10 (27% of 37) are LIA missions; 5 (14% of 37) are MIA missions; 20 (54% of 37) are HIA[26] missions. Figure 6 shows 37 LEO mission inclination angle distribution.

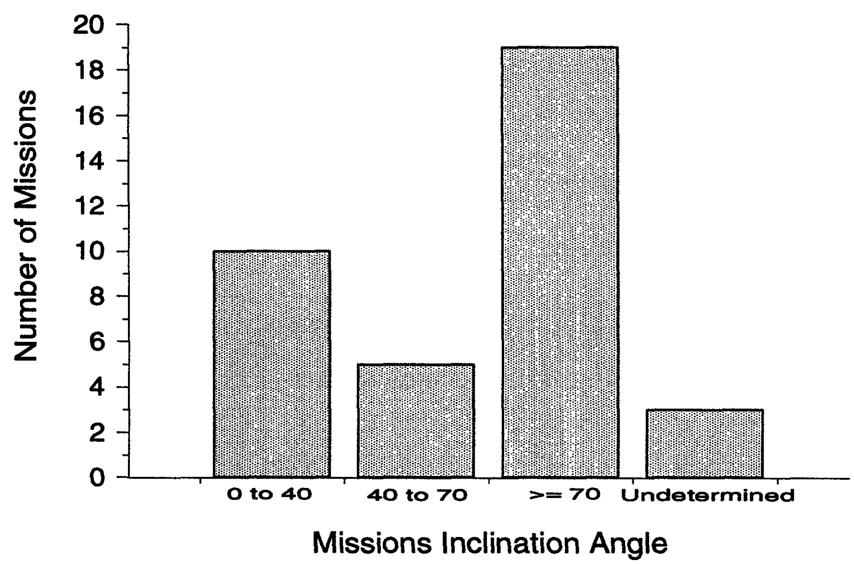

Figure 6: 37 LEO missions inclination angle distribution.

[25] Due to free space loss, the difference in signal strength is 20×log(7901/1944)=12.18dB.
[26] The inclination angles of ACME 1 and ACME II have not been determined.

The inclination angle distribution is consistent with the figures suggested in the DSN long range plan study [8] aforementioned. Each LEO mission group has its own optimal ground terminal location for telemetry downlink. In general, LIA missions experience longer available view periods when supported at low latitude ground sites. Similarly, MIA missions are better supported at moderate latitude ground sites and HIA missions at high latitude ground sites. The DSN 26m subnet (±30° and 40° latitude) locations are excellent for supporting MIA missions. They can be used to support LIA or HIA missions, but with very poor network visibility compared with either lower or higher latitude ground sites, especially for LIA missions. Table 3 show the inclination angle distribution for the 10 LEO missions.

Inclination Angle	LIA	MIA	HIA
# of Missions	5	1	4

Table 3: 10 selected LEO missions inclination angle distribution.

Most remote-sensing LEO missions require only non-real time telemetry downlink (tape replay or solid state memory dump), utilizing on-board storage. Only a few missions, such as XTE, may require real time telemetry downlink during their prime mission phase due to remote-sensing instrument characteristics, mission objectives, and requirements. For missions that are only required to perform non-real time data dump, the required contact time per day is determined by the mission data volume[27] and the preset downlink data rate. Table 4 shows the 10 LEO mission downlink data rate distribution.

Maximum Telemetry Downlink Data Rate	LEO Missions
Below 256 kbps	IRTS, SAC-B, TOMS-EP
512 kbps	EUVE, GRO
900 kbps	FAST, SAMPEX
Above 1024 kbps	SASSE, SWAS, XTE

Table 4: Date downlink rate for 10 LEO missions.

Requested contact time has direct influence on LEONET performance. Some missions require longer contact time while others require shorter ones. The longest contact time

[27] The data volume is the total amount of data collected by the remote-sensing instruments during a day.

among these 37 LEO missions is 480min/day while the shortest one is only 8min/day[28]. Table 5 shows the total non-real contact time per day and Table 6 shows the required number of passes for each of the 10 LEO missions.

Total Contact Time Per Day	LEO Missions
0 to 29 Min.	SAC-B, SAMPEX, SASSE, SWAS
30 to 59 Min.	GRO, XTE
60 to 89 Min.	IRTS, TOMS-EP
90 to 119 Min.	EUVE
120 Min. and over	FAST

Table 5: 10 LEO mission total non-real contact time distribution.

Given the same network configuration, longer requested mission contact time results in higher network lost time percentage because of higher probability of experiencing mission-to-mission conflict.

Required Number of Passes Per Day	LEO Missions
2 Passes	SAC-B, SAMPEX, SASSE
3 Passes	GRO, SWAS, XTE
6 Passes	IRTS, TOMS-EP
9 Passes	EUVE, FAST

Table 6: Required number of passes per day for 10 LEO missions.

The selected set of missions under study should provide enough link margins (carrier margin and data margin) when their telemetry data is received with LEO-D type small aperture ground receivers. Link analysis of the Design Control Tables (DCTs) for each LEO mission is used to determine their data margin and system G/T when supported by a 3m antenna LEO-D type terminal.

Required Antenna Aperture Size	LEO Missions
At 5 deg Elevation angle: Smaller than 3m	IRTS, TOMS-EP
At 5 deg Elevation angle: About 3m	EUVE
At 5 deg Elevation angle: Larger than 3m	FAST, GRO, SAC-B, SAMPEX, SASSE, SWAS, XTE

Table 7: Required aperture size for 10 LEO missions.

The preliminary link analyses results are obtained with the worst case mission link parameters (for example, highest data rate[29] and lowest antenna gain[30] are used during

[28] For some LEO missions, decisions on the required contact time have not been made. The shortest and the longest contact time are extracted from the available ones in 37 missions.
[29] Spacecraft usually accommodate several data rates for telemetry downlink.

simulation). The actual system performance are expected to be better because worst case parameters may not appear at the same time. The resulted required antenna aperture size for each mission is shown in Table 7.

Mission link parameters may not be up-to-date. At times, the spacecraft performance for current in-flight missions decreases with flight time due to components aging. For future missions, spacecraft parameters may not be permanently set. Further link analyses are desired to guarantee that successful telemetry downlink can be established from spacecraft to LEO-D terminal. Results of the preliminary link analysis are summarized at the end of this chapter in Table 8 to Table 10.

When mission data margin is less than 3dB, one tradeoff that can be considered is to increase the receiver antenna aperture size. Increasing the antenna diameter from 3m to 4m and from 3m to 5m results in a 2.5dB and a 4.44dB increase in antenna gain respectively. The increased antenna gain can be directly applied to both carrier and data margin in the link analysis. The LEO-D type terminal antenna aperture size can be increased to accommodate the weak downlink signals from some LEO missions.

2.2 Brief Profiles of 10 Selected LEO Missions

After considering the two main criteria, which are presented in the beginning of this section, and other practical factors, 10 missions have been selected from the 37 LEO mission pool. They are EUVE, FAST, GRO, IRTS, SAC-B, SAMPEX, SASSE, SWAS, TOMS-EP, and XTE. These 10 typical LEO missions are good representatives of the 37 LEO missions as well as all current and future NASA LEO missions. Their detailed mission orbital and link parameters are presented in Table 8 to Table 10. Each individual mission is briefly described in this section. Additional information as well as concerns for each mission are discussed. All 10 missions utilizing S-Band downlink. The nominal downlink frequencies vary from 2215MHz to 2287.5MHz.

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[30] Even omni directional antennas do not have the same antenna gain for all directions. In one direction the antenna gain is larger than the other directions. Usually, the further off the bore sight (the angle with the highest gain), the worse the antenna gain.

Missions	Launch Date	End Prime Mission	End Ext Mission	Perigee (km)	Apogee (km)	Inclination (deg)
EUVE	06-01-1992	01-01-1996	01-01-2000	528.00	528.00	28.45
FAST	08-23-1994	09-30-1995	12-31-1999	350.00	4200.00	83.00
GRO	04-05-1991	04-05-1993	TBD	450.00	450.00	28.50
IRTS	01-01-1995	07-02-1995	TBD	400.00	500.00	97.00
SAC-B	12-01-1994	11-30-1997	11-30-1998	550.00	550.00	38.00
SAMPEX	06-12-1992	07-30-1995	12-30-1999	514.00	692.00	82.00
SASSE	01-01-1997	01-01-1999	TBD	504.00	504.00	0.00
SWAS	06-01-1995	06-30-1998	12-30-1999	600.00	600.00	65.00
TOMS-EP	07-01-1994	07-31-1996	07-31-2000	955.00	955.00	99.28
XTE	08-01-1995	07-31-1997	08-31-2000	600.00	600.00	23.00

Table 8: 10 selected LEO mission set parameters, part (a).

Missions	Downlink Freq (MHz)	Downlink Rate (kbps)	Passes Per Day	Contact Per Pass (min)	RF Power (W)	Slant Path (km)	Free Space Loss (dB)
EUVE	2287.50	512.00	9	10	5.00	2150.24	166.28
FAST	2215.00	900.00	9	20	5.00	7901.38	177.30
GRO	2287.50	512.00	3	10	5.00	1944.48	165.40
IRTS	2263.60	128.00	6	10	5.00	2077.96	165.89
SAC-B	2255.50	200.00	2	8	5.00	2205.90	166.38
SAMPEX	2215.00	900.00	2	10	5.00	2544.95	167.46
SASSE	2215.00	1800.00	2	8	5.00	2088.39	165.74
SWAS	2215.00	1800.00	3	8	5.00	2329.03	166.69
TOMS-EP	2273.50	202.50	6	10	3.00	3105.16	169.42
XTE	2287.50	1024.00	3	10	5.00	2329.03	166.97

Table 9: 10 selected LEO mission set parameters, part (b).

Missions	Ant Gn (dB)	Ckt Loss (dB)	Un/coded	Req Eb/No (dB)	Carrier Performance margin (dB)	Data Margin 3-meter(dB)	Data Margin 5-meter(dB)
EUVE	0.20	-8.90	Uncoded	9.68	27.74	3.19	7.63
FAST	-5.00	-0.50	R=1/2,7,Conv	4.46	26.63	-5.15	-0.71
GRO	-1.00	-4.80	Uncoded	9.68	33.72	2.57	7.01
IRTS	-8.00	-2.50	Uncoded	9.68	29.76	5.59	10.03
SAC-B	-7.00	-6.00	Uncoded	9.68	23.21	-0.26	4.18
SAMPEX	-7.00	-1.60	R=1/2,7,Conv	4.46	24.84	2.08	6.52
SASSE	-7.00	-1.60	R=1/2,7,Conv	4.46	26.57	0.80	5.24
SWAS	-8.00	-1.00	R=1/2,7,Conv	4.46	25.22	-0.55	3.89
TOMS-EP	0.00	-2.70	R=1/2,7,Conv	4.46	28.34	10.04	14.48
XTE	0.00	-7.20	Uncoded	9.68	28.54	-2.02	2.42

Table 10: 10 selected LEO mission set parameters, part (c).[31]

[31] The carrier performance margin is the excess carrier margin over the 12dB carrier margin required by CCSDS. The actual carrier margin is = carrier performance margin + 12dB.

Extreme Ultraviolet Explorer (EUVE)

EUVE is currently in its prime mission phase. A research team at University of California at Berkeley is studying a low cost network to support EUVE during its extended mission phase. With its omni antenna, EUVE provides a 3.19dB telemetry downlink data margin when supported by the LEO-D 3m antenna terminal. The current LEO-D project is also demonstrating the ability to receive data downlink from EUVE and is scheduled to take place early 1995 with a spread spectrum receiver.

EUVE has two tape recorders, each having 2 tape units with 1000ft of tape (500ft in each direction). The tapes move at ~0.28in/s and record at 32kbps. There are 24hrs$\times$ (60min/hr) $\times$(60s/min)=86,400s/day. That gives the maximum of 350Mbytes gathered data per day. At 512kbps downlink data rate, the data can be dumped to ground receivers in approximately 90min. If 256kbps downlink rate is utilized and assume no spacecraft gathered data is lost, the total required contact time would be twice as long.

Currently, one of the EUVE power amplifiers is malfunctioning and its omni antenna is not in use. The transponder transmits a spread spectrum signal through its High Gain Antennas (HGA). This signal requires a spread spectrum receiver which might increase the cost of network and cause further technical problems. However, during the extended mission phase, it is likely that the transponder will transmit non-spread spectrum signals through its omni antenna.

Whether the HGA or omni antenna of EUVE is in use affects the available downlink data rate and consequently the total required contact time. For the time being, the assumption is made that EUVE uses its omni antenna to transmit with a 512kbps downlink data rate.

Fast Auroral Snapshot Explorer (FAST)

FAST is the only selected mission with highly elliptical orbit. Convolutional coding is utilized on its telemetry data downlink. Hence the required E_b/N_o is also reduced. DSN is only required to support FAST at a selectable downlink data rate up to 900kbps. At this data rate, a 7.8m antenna is needed to give a 3.1dB channel data margin. The highly elliptical orbit provides relatively long view period duration when FAST is viewed at low latitude ground sites even though it is a HIA mission. It does not necessarily need to be supported at high latitude sites.

Due to its 350km×4200km orbit, FAST experiences high velocity when it is approaching its perigee. Receiving antennas with high slew rate are required to match up with the high spacecraft velocity. Small aperture antennas have advantages over large aperture antennas because the former provide much higher slew rate.

Gamma Ray Observatory (GRO)

GRO and EUVE have similar orbits. GRO is currently in its extended mission phase. It has the lowest altitude among all 10 LEO missions. A 3.2m antenna is necessary to obtain a 3.13dB data margin.

Infrared Telescope in Space (IRTS)

This infrared telescope is on board of Space Flyer Unit 1 (SFU-1). This mission is a joint effort between NASA and ISAS (Japanese Space Agency). The rather low 128kbps downlink data rate yields a 5.59dB data margin when received by a 3m LEO-D terminal. The telemetry data is not encoded. With very high inclination angle and low altitude, the IRTS downlink requirement creates a problem for LEONET when it is supported by a low latitude ground stations.[32] Even high latitude ground stations can experience difficulty when supporting IRTS's six 10min passes (6×10)[33] required contact time. The LEONET performance as a whole depends on to which ground station IRTS load is applied. The optimal ground terminal locations for supporting IRTS and its implications load distribution scheme are discussed in Chapter 5.

Satellite de Aplicaciones Cientificas-B (SAC-B)

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[32] The higher the satellite inclination angle, the less time it can be viewed at low latitude ground stations. Furthermore, the lower the satellite altitude, the smaller its footprints on Earth, and hence the shorter the view period for each of its pass at that ground station.

[33] "Six 10min passes" is represented as 6×10, so on and so forth, throughout this report.

SAC-B is a joint mission between NASA and Argentina. Because of its low inclination angle, GSFC and Wallops cannot provide the required coverage. A 12ft (3.66m) small aperture ground terminal is being built at a low latitude site in Argentina to help supporting the mission telemetry downlink. SAC-B has a relatively low 200kbps data rate and a short 8min required contact time[34]. From link analysis, to obtain the required 3dB data margin for supporting SAC-B, a 4.37m (14.4ft) antenna is needed. The discrepancy in aperture size between the 14.4ft antenna and the 12ft aperture antenna designed in Argentina may be introduced by differences in minimum elevation angle requirement, data margin requirement, and other link parameters used in the link analysis.

Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX)

SAMPEX is the first SMall EXplorer (SMEX) missions supported by GSFC for NASA. It is currently in its prime mission phase. The LEO-D project has successfully demonstrated the telemetry data acquisition from SAMPEX with the 3m aperture LEO-D terminal located on top of Mesa at JPL, at both 900kbps and 32kbps downlink data rate. The received data has been LZ processed and tested, and the test results verify the functionality of the receiver. The LEO-D terminal has also successfully demonstrated its automated data distribution capability with this SAMPEX. The data margin obtained in the LEO-D project with 10° elevation angle is 4.28dB. However, at 5° elevation angle, a 3.33m antenna is necessary to satisfy the required 3dB data margin.

Small Astrophysical & Solar Spectrometer Explorer (SASSE)

SASSE is one of the few satellites with equatorial orbit due to the constraints of the on-board remote-sensing instrument operation. It is proposed to be launched in 1997. The mission will be supported by JPL. The rather high latitude DSN 26m subnet stations cannot view this satellite. SASSE needs a ground terminal close to the Earth's equator to support its DTG telemetry data downlink. TDRSS can be utilized to support SASSE but it has numerous disadvantages when compared with low cost and high efficiency small aperture LEO-D type terminals.

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[34] During the simulations, the required contact time has been conservatively increased to 2×8.

SASSE will utilize NASA standard transponder, but antenna parameters and its interface to the transponder have not been fully determined. However, it is believed that SASSE antenna and its interface will be similar to those of SAMPEX. Thus, SAMPEX antenna circuit loss and antenna gain parameters have been used in the preliminary link analysis for SASSE. SASSE has proposed a 1.8Mbps downlink data rate and a 10min required contact time[35] per day. Since the maximum view period length at the Earth's equator (0° latitude) is only 9.9min at 5° elevation angle and only 8.5min at a 10° latitude site, the contact time has been modified into 2 passes, each with a shorter contact time of 8min. Thus, the total of 2×8 contact time per day is used for SASSE during the analysis. A 3.9m antenna is needed to provide a 3.08dB data margin.

The actual antenna and its interface parameters for SASSE can be, and probably will be different from the ones assumed. If the actual parameters are not good enough to provide the required 3dB data margin, besides increasing antenna aperture size, another tradeoff can be considered to increase data margin. Its 1.8Mbps telemetry data rate can be reduced in exchange for a longer contact time. Since SASSE is an equatorial mission, it experiences a pass over an equatorial (or a very low latitude) ground station for every orbit. Hence scheduling downlink passes is not a difficult problem. Because the total data volume is fixed by the instrument readout rate, with ample amount of contact time, the data rate can be lowered without affecting the total data return rate. Lower data rate will result in a higher received signal power and consequently a higher data margin.

Submillimeter Wave Astronomy Satellite (SWAS)

SWAS is a future SMEX missions. Total required contact time is assumed to be 3×8 even though there is another document quoting a 4×6 required contact time. A 4.5m antenna is necessary to give a 3dB data margin. The predicted poor link margin with a 3m antenna receiver is partially due to its rather high 1.8Mbps downlink data rate. The actual downlink data rate that will be used during normal telemetry downlink is likely to be

[35] The total required contact time is suggested by PI with the considerations on instrument readout rate, on-board memory size, and downlink data rates.

900kbps. In this case, the antenna aperture size needed to maintain a 3dB data margin would decrease.

Total Ozone Mapping Spectrometer-Earth Probe (TOMS-EP)

TOMS-EP was launched into orbit in July, 1994. It has high omni antenna gain, rather low 202.5kbps data rate, and the Convolutional channel encoding. Even though it has only a 3W RF power, it provides an adequate 10.04dB data margin with the 3m antenna LEO-D terminal due to its low data rate and encoding scheme. Even though there also are documents showing that the required contact time for TOMS-EP are 4×18, 4×15, and 6×12, the 6×10 contact time is used in the analysis. The altitude of TOMS-EP is almost twice as high as that of IRTS. It gives TOMS-EP longer view period duration at both low and high latitude sites[36] compared to IRTS.

X-ray Timing Explorer (XTE)

XTE is scheduled to be launched into space in August, 1995. Its poor link margin is partially due to its rather high 1024kbps downlink data rate and also a very high 7.2dB antenna circuit loss (interface between antenna and transponder). A 5.35m antenna LEO-D receiver is necessary to obtain the 3dB data margin at the 5° elevation angle.

During its 2 year prime mission phase, XTE will utilize TDRSS to support its real time telemetry data downlink due to XTE's mission objectives and characteristics. During the first year observing period, instantaneous interactions between spacecraft, mission control, and PIs are necessary. Mission control operators and staff scientists will be working around the clock to monitor the returned data. However, during the second year of the prime mission phase, there is a possibility that 3 shift support will be reduced to 2 shifts due to mission budget constraints. In that case, about 1/3 of XTE telemetry data will be recorded and then returned to a ground terminal. After the 2-year prime mission phase, all XTE data will be delivered utilizing recorded data dump. XTE fills up its 1 Mb solid state

[36] TOMS-EP information is obtained from GSFC DOC531-GSA-TOMSEP.

memory every 4 orbits. It has multiple downlink data rates. Both 1024kbps and 512kbps are likely to be used for telemetry data downlink[37].

2.3 Conclusion

5° minimum elevation angle is assumed throughout the link analyses and also the view periods generation for all missions. Theoretically, 0° minimum elevation angle (horizon-to-horizon) could give longer mission view periods. However, 5° minimum elevation angle is adopted because of land mask (a geometric limitation such that a site does not have a horizon-to-horizon view of sky) as well as limitation on signal strength due to free space loss. Lowering the minimum elevation angle from 5° to 0° also increases both atmospheric attenuation ($A(\theta)$) and weather-temperature-increase for noise temperature. They both hamper the spacecraft signal strength. $A(\theta)$ as a function of elevation angle θ is shown in Equation 1,

$$A(\theta)=\frac{2*A_{zenith}}{Sin^2\theta+\sin\theta+0.02354} \qquad \textbf{Eq. 1}$$

where A_{zenith}=0.038dB. At 5° elevation angle, $A(5°)\approx0.78$dB. At 0° elevation angle, $A(0°)\approx32.34$dB. Moreover, weather-temperature-increase rises from 25K at 5° elevation angle to 112K at 0° elevation angle, which results in another 1.6dB loss in signal strength[38]. Lowering elevation angle also increases maximum slant path from a spacecraft to a ground station and consequently increases the free space propagation loss, which also weakens the spacecraft signal strength.

The 3m LEO-D terminal cannot successfully provide the required 3dB data margin for 7 of the 10 LEO missions at the 5° elevation angle. The data margin as a function of system G/T for the 10 LEO missions is shown in Figure 7. System G/T is given in Equation 2,

$$G/T=G_{Antenna}(dB) - 10\times\log T(dB) \qquad \textbf{Eq. 2}$$

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[37] Information is obtained from a private conversation with Otto Bruegman at GSFC.

[38] Assuming system operating temperature is 170K. The loss of signal strength is 10×log(170K+112K)-10×log(170K+25K)=1.6025dB.

where T=195K is the predicted system temperature at 5° elevation angle.

As aforementioned, a 4m and a 5m antenna have a 2.5dB and a 4.44dB increase in antenna gain from a 3m dish respectively. A 6m and a 7.8m dish each has a 6.02dB and a 8.25dB better gain than a 3m antenna respectively. This rough estimation is under the assumption that antenna efficiency is a constant if the aperture size does not change on the order of magnitude. At the 195K system operating temperature, a 3m dish has a G/T=11.35dB/K, a 4m dish has a G/T=13.85dB/K, a 5m dish has a G/T=15.79dB/K, a 6m dish results in a G/T=17.37dB/K, and a 7.8m dish has a G/T=19.6dB/K.

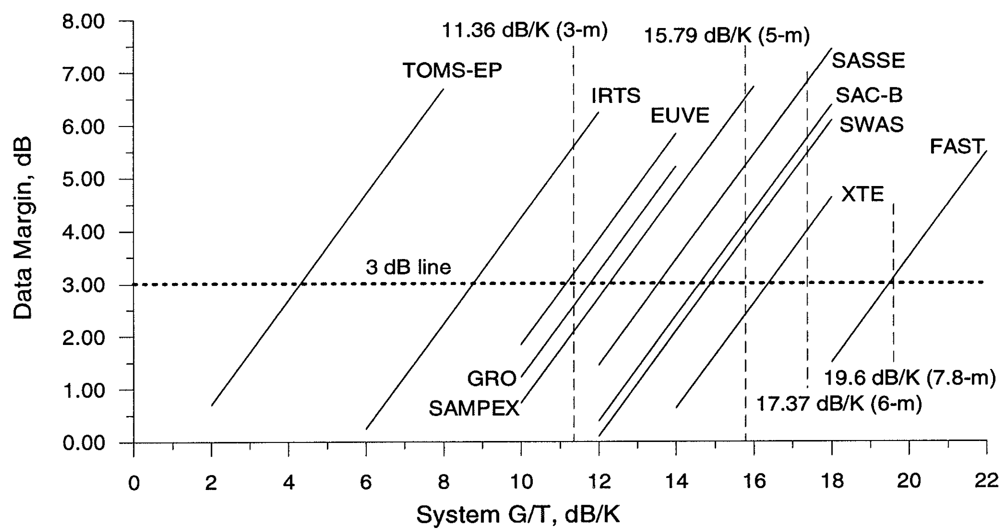

Figure 7: LEO mission set data margin vs. system G/T at 5° elevation angle and T=195K.

3 of the 10 LEO missions have data margins larger than 3dB when supported by a 3m aperture LEO-D type terminal. 8 of the 10 LEO missions can be supported with a 5m aperture LEO-D type terminal. It is necessary to have a larger aperture (~8m) antenna if all 10 LEO missions data downlink are to be supported by the LEO-D type terminal.

Chapter 3 LEONET Simulation Tool

3.1 Introduction

All space missions can be categorized as either deterministic missions or non-deterministic missions. Deterministic missions refer to the ones whose classic 8 orbital elements are well-known throughout a long forecasting interval. The 8 orbital elements, Epoch day, Decaying rate, Inclination angle, Right ascension of ascending node[39], Eccentricity, Argument of perigee, and Mean anomaly [9], specify exactly where the spacecraft is and where it is going to be in the future. The opposite are non-deterministic missions. The majority of the deep space missions are considered deterministic missions mostly due to their relatively long orbit periods and weaker secondary effects from the Earth and the moon. LEO missions are non-deterministic mainly because of their shorter orbit periods and stronger Earth and Lunar secondary effects.

TERASCAN, a software package developed at Sea Space Corporation, PC-TRACK, an orbit simulation tool developed by Thomas C. Johnson and Acme Workshop, as well as the Planetary Orbiter Planning Software (POPS) program, developed at JPL in Section 314, can be used to perform scheduling for deterministic missions. Based on their computation models, these programs propagate the mission orbital trajectories over the entire forecasting interval, through which the mission view periods at a ground station location can be obtained. The subnet baseline loading curve, the mission-to-mission conflict, and the subnet lost time percentage at that ground location can be consequently calculated from these mission view periods. However, when utilized to forecast the average load condition and mission-to-mission conflict at a ground station over a long forecasting interval, these simulation tools become very cumbersome to use. First, simulations have to be performed over the entire long forecasting interval, which takes a

[39] The ascending node is the other component besides the inclination angle that specifies the satellite's orbital plane. During each orbit the satellite crosses the equatorial plane twice. The point where the satellite crosses the equatorial plane from south to north is called the ascending node. The location of the ascending node is specified by the angle, right ascension of the ascending node, in a geocentric system.

huge amount of simulation time and computing power. Second, simulations need to be performed for a series of different mission orbit starting positions in order to obtain the view periods and their associated probabilities. The simulations are both time consuming and labor intensive.

Furthermore, for a simulation over a long forecasting interval, LEO missions have to be treated as non-deterministic missions (unless they are in controlled orbits such as GPS and TOPEX). The short orbital periods of LEO missions make their mission orbital trajectories very vulnerable to Earth, Lunar, and Solar (primarily due to atmospheric drag, Solar pressure, and gravitational effect) effects [10], which have not been completely and accurately modeled in deterministic simulation tools. For current in-flight missions, orbits can only be accurately predicted up to 3 weeks ahead of time. Periodic tracking is necessary to locate LEO satellites and to produce precise trajectory data for antenna pointing purposes. Due to the uncertainties in satellites' trajectories, the mission-to-mission relative locations also change over time. Depending on mission orbital parameters, their relative positions can change dramatically and ultimately influence the ground station mission-to-mission conflict analysis[40]. For future missions, because of aforementioned effects as well as the uncertainties in initial deployment parameters (including both time and position), it is not possible to accurately predict the location of a LEO satellite for a certain time in the future, nor the accurate mission rise and set time[41]. Consequently, mission-to-mission conflict cannot be accurately obtained.

Due to the orbit uncertainties and the lack of correlation information on LEO mission trajectories, it is impossible to know which LEO missions may require telemetry downlink at the same time during a long forecasting interval. The lack of information on the correlation of successive mission view periods hampers the ability to accurately predict

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[40] One might argue that the missions relative position may change very little over time because the secondary effects are very small. However, LEO missions have very short orbital periods which allow the relative position changes to be more noticeable. Moreover, mission inclination angles and eccentricities add another 2 degrees of freedom that aggregate the change of relative position between missions.

[41] For a LEO mission, the rise time is the time the spacecraft can be viewed at a ground station. The set time is the time the spacecraft is moving out of the ground station' view. The difference between the set time and rise time is the mission view period for that orbit.

antenna and subnet loading. Thus, using deterministic analysis tools to propagate the mission orbit trajectories and then to obtain mission-to-mission conflict and to forecast antenna load becomes a "meaningless" practice.

Because of the inherent non-deterministic characteristic of LEO missions, a simulation tool with a stochastic approach is desired in order to tackle station load condition and mission-to-mission contention more efficiently. LEO4CAST, a software package developed at JPL in Section 311, is such a simulation tool. It has been used in Section 311 to perform DSN long term capacity forecasting for Near Earth and Deep Space missions. It has recently been modified to accommodate non-deterministic missions for the uncertainties in both mission orbits and other secondary effects not included in the simulation model. Because of its probabilistic approach, LEO4CAST can solve the problem of long term network capacity and mission contention analysis more efficiently than other deterministic simulation tools. The main difference between LEO4CAST and other deterministic simulation tools can be summarized as follows. LEO4CAST is designed to forecast the expected ground station load condition, the expected mission-to-mission conflict, and their associated probability of occurrence over a long forecasting interval, while other deterministic simulation tools are designed to accurately predict mission orbit trajectories, instantaneous ground station load condition and mission-to-mission conflict at a given time in the future. LEO4CAST reduces both the required computing power and the simulation time. Because of these advantages, LEO4CAST is adopted as the core computing element of the LEONET optimization analysis. The deterministic tools can be used to verify the simulation results and to raise confidence level in LEO4CAST's stochastic analysis approach [11].

However, LEO4CAST ignores the secondary effects on mission orbits and the mission requirements on minimum and maximum time between downlink contacts. The longitude effects of ground sites have been averaged out during the simulation. It is necessary to point out that LEO4CAST itself does not perform system optimization. It is the entire procedure, which incorporates LEO4CAST as its core engine, that performs the optimizations.

The averaging technique in LEO4CAST is not the "perfect" way to analyze load duration and mission-to-mission conflict. For the time being, LEO4CAST does not have the ability to screen requirements of minimum or maximum time between downlink contacts, which depends on the spacecraft on-board storage and ground uplink resources. Similarly, the exclusion of existing correlations between successive mission view periods and that between ground stations increases the difficulty in the optimization of the network load distribution schemes during the analysis. However, LEO4CAST is still more efficient for the LEONET analysis than other deterministic simulation programs.

3.2 LEO4CAST Program Fundamentals

The LEONET ground station quantity and locations optimization consists of network station capacity analysis, which in turn requires the estimate of mission-to-mission conflict in addition to individual mission requirements. LEO4CAST simulation is the tool to perform mission contention analysis. It is intended to simulate the ground station load condition and mission-to-mission conflict for specific missions at a specific ground station. The reason that a stochastic simulation tool, such as LEO4CAST, can be successfully used to perform the long term forecasting for non-deterministic missions is that the spatial average of the expected mission view periods is approximately equal to the time average of the expected mission view periods.

LEO4CAST can be used to generate the expected mission view periods. LEO4CAST utilizes the same 8 fundamental orbital trajectory equations (Appendices 7.1) as other deterministic simulation tools do. But unlike the deterministic tools, which take orbital information to propagate their trajectories throughout the simulation interval, LEO4CAST calculates the expected mission view periods for a series of orbits with different orbit starting points (ascending nodes). The resolution of this series of ascending nodes is controlled by the user. In this manner, a statistical trajectory database can be obtained for repeated use. LEO4CAST associates each view period length with the probability of its occurrence, and uses them to calculate the probabilities of mission-to-mission conflict.

Utilizing the statistical information in addition to mission orbital information and telemetry downlink requirements, LEO4CAST constructs ground station Load Duration Curves (LDC). LDC represents the average ground station load levels and the expected view period length for missions supported at that ground station. From the statistical results, particularly the expected view period lengths and their associated cumulative density functions, LEO4CAST generates the LDC files which are used to forecast the ground station capacity and to analyze the subnet lost time percentage due to mission contention.

Due to the uncertainty in the inter-mission orbital correlation over a long forecasting interval, the statistical independence[42] of mission view period lengths is assumed. Because of the assumed statistical independence, it is the same as saying that the expected total view period ratio (total view period duration over the entire long forecasting interval) is the sum of the individual view period ratios. The subnet lost time directly results from the overlap of the expected individual mission view periods.

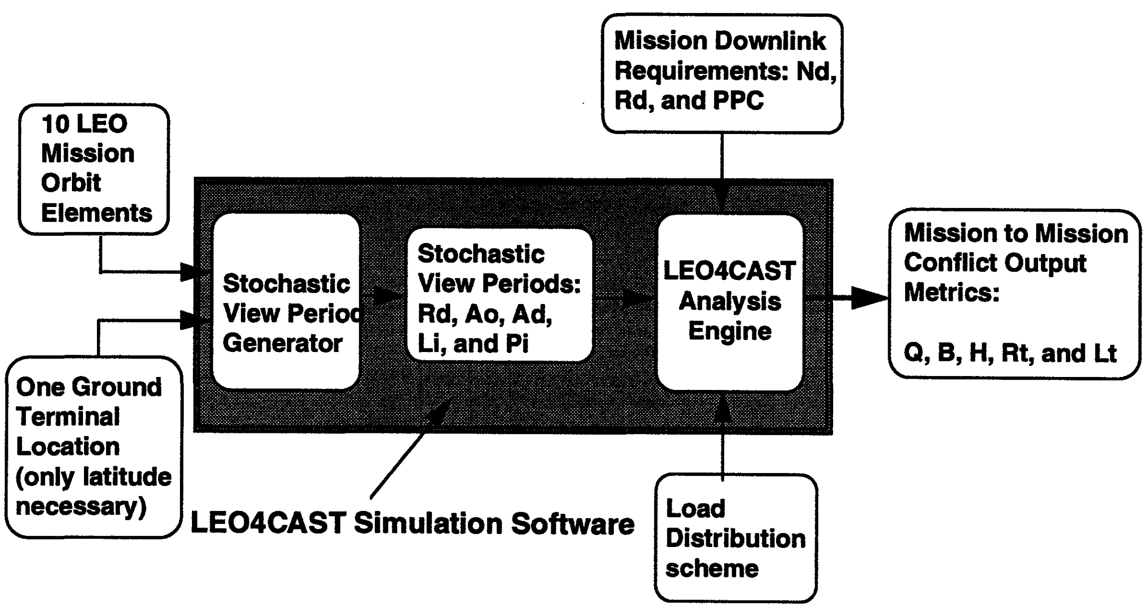

Figure 8: LEO4CAST simulator architecture.

LEO4CAST takes mission apogee, perigee, and inclination angle to obtain the view period lengths for that mission at a specified ground station and their associated probabilities,

[42] There is a minimum time interval before which the statistical independence of mission view period lengths can be considered valid. For the purpose of this study, we assume the forecasting interval is longer than this minimum time interval.

utilizing numerical integration. First, a series of evenly spaced ascending nodes are selected at user specified resolution. Since the inclination angle and ascending node specify a satellite's orbital plane, the view period at a specific ground station for each ascending node then can be numerically found. Because only the long term average of mission view periods is important for the analysis, the time average of mission view periods can be essentially approximated as the spatial average (at different ascending nodes) of mission view periods [12]. Figure 8 shows the architecture of LEO4CAST, its inputs and its outputs. LEO4CAST takes mission orbit and ground station parameters to generate mission view periods and other intermediate results. Along with mission telemetry downlink requirements and load distribution scheme, the average mission view periods and the intermediate results are used to produce mission-to-mission conflict probabilities.

LEO4CAST software is written in Borland C++, and it is set up to run on a 486/33 PC platform. The simulation takes from several minutes to several hours[43] depending on the number of LEO missions and ground stations modeled in the simulation. The simulation outputs are analyzed using Microsoft EXCEL, and GRAPHER for Windows, from which graphs and charts are generated.

3.3 LEO4CAST Key Metrics

In order to analyze LEO4CAST output files, a set of performance metrics needs to be specified. The following subsections describe the symbols, definitions, and notations that are frequently used in this analysis.

3.3.1 Ground Site Quality Factor

The network performance analysis determines which ground station locations will result in the maximum view periods for the LEO missions they support. Missions view period is the duration when a spacecraft can be viewed at a ground station. It is the difference

[43] LEO4CAST consumes much less time than other deterministic simulation tools which might have to run for several hours or even days to complete one such simulation.

between the rise time and set time. To measure how effectively a ground station can support a mission, a ground station location quality[44] factor Q is introduced. The following are the definitions and notations involved in the calculation of Q.

N_d	mission requested number of passes per day at one ground site
R_p	mission requested contact time per pass.
PPC	pre- and post- calibration time for ground terminals
L_i	mission view period length at a ground site
P_i	probability associated with each view period length L_i
R_d	required mission contact time per day (including PPC) at one ground site
A_o	expected available mission contact time per orbit at one site
A_d	expected available mission contact time per day at one ground site
Q	a difficulty measurement for a ground site to support individual mission

R_d can be found from N_d, R_p, and PPC. Specifically, R_d is given by Equation 3.

$$R_d = N_d \times (R_p + PPC) \qquad \textbf{Eq. 3}$$

A_o can be obtained from L_i and P_i, where i is the reference index to each view period. The step size of view period lengths is specified by users. For example, if the available view period lengths vary from 6min to 11min and if the specified step size is 0.5min, there will be 11 available view period lengths where i=1 to 11. A_o is given by Equation 4.

$$A_o = \sum_i (P_i \times (L_i + PPC)) \qquad \textbf{Eq. 4}$$

A_o refers to the available contact time per orbit, from which the available contact time per day, A_d, can be obtained. It is given in Equation 5.

$$A_d = \frac{A_o}{\text{Number of Orbits Per day}} \qquad \textbf{Eq. 5}$$

Thus, Q, the measurement of how difficult it is for a particular ground station to support the telemetry downlink requirements of a LEO mission, is defined as the ratio of R_d and A_d and is shown in Equation 6.

[44] "Difficulty" probably is a more appropriate word than "quality." Q is the factor that measures how difficult it is for a ground station to support LEO missions. The smaller Q is, the better the ground station's ability to support LEO missions. However, since "quality" is frequently used in LEO4CAST, it is also used in this report.

$$Q = \frac{R_d}{A_d} \quad \textbf{Eq. 6}$$

P_i, which is associated with each L_i, changes with the latitude of ground station location for a given mission. With a fixed R_d, the larger the A_d, the smaller the Q because more available contact time results in less probability of mission-to-mission conflict. Moreover, changes in the mission requirements directly or indirectly affect Q. Raising either N_d or R_p increases R_d and consequently Q if all other parameters are held constant[45]. PPC affects Q in a more subtle way. Both the denominator A_d and the numerator R_d in Equation 6 are strong functions of PPC. Depending on other parameters that affect A_d and R_d, the change in PPC can either increase or decrease Q. It is found for the set of A_d and R_d used in this analysis, the influence from PPC on Q is negligible.

i	Li(min)	Pi	Li*Pi	Pi*(Li+PPC)
1	6.00	0.0167	0.1000	0.3000
2	6.50	0.0167	0.1083	0.3083
3	7.00	0.0222	0.1556	0.4222
4	7.50	0.0333	0.2500	0.6500
5	8.00	0.0278	0.2222	0.5556
6	8.50	0.0389	0.3306	0.7972
7	9.00	0.0500	0.4500	1.0500
8	9.50	0.0833	0.7917	1.7917
9	10.00	0.0361	0.3611	0.7944
sum of Pi		0.3250		
sum of Li*Pi			2.7694	
sum of Pi*(Li+PPC)				6.6694

Table 11: Sample LEO4CAST view period outputs used to generate Q.

The following illustrates how LEO4CAST generates Q, for the case of EUVE being supported at Koror Island (0°, 0°). EUVE has orbit period = 94.937min, R_p=10min, N_d=9, and PPC=12. The LEO4CAST generates EUVE View Period Lengths (L_i) and

[45] In LEO4CAST mission contention analysis, if the expected view period length for a mission at a site is smaller than the required 8min minimum contact time per pass, the expected view period at this site is set to zero. From the definition, the ground site quality factor should consequently become infinite. However, LEO4CAST sets the ground site quality factor to zero and does not include this mission in the contention level analysis. It is the users' responsibility to make sure that a mission can be supported by a ground site before it is included in the mission contention level simulation.

their associated Probability (P_i) which are shown in Table 11. $P_i \times L_i$, $P_i \times (L_i + PPC)$, ΣP_i, $\Sigma P_i \times L_i$, and $A_o = \Sigma(P_i \times (L_i + PPC))$ are calculated from L_i and P_i for i=1 to 9.

Thus, the Expected View Period Length is $\frac{2.7694}{0.325} = 8.52 \text{minutes}$. Since

$$R_d = 9 \times (10 + 12) = 198 \text{ minutes, and}$$

$$A_d = \frac{6.6694 \times (24 \text{ Hours}) \times (60 \text{ Minutes / Hour})}{94.937} = 101.16,$$

the quality factor of Koror Island to support EUVE is $Q = \frac{198}{101.16} = 1.96$.

LEO missions' main objectives are to collect data from remote-sensing instruments and then transfer the data to ground stations. LEONET performance is measured primarily by the ratio of the amount of scientific data that the network can receive from a spacecraft to the total amount of scientific data a spacecraft generates, which is equivalent to the ratio of the available contact time to the requested contact time. Q is one of the major network performance metrics. When Q>1, the required contact time is longer than the available contact time. Scientific data will then definitely be lost in the network. When Q≤1, the requested contact time for an individual mission is less than the available contact time. However, the network may still lose scientific data due to mission-to-mission conflict. In LEONET analysis, network optimization is to have Q≤1 and also minimize the network lost time percentage, which is another metric for network performance. Clearly, for the above example where Q=1.96, one ground terminal at Koror Island is not sufficient to support the EUVE downlink requirement. If there are 2 ground terminals, the average Q=0.98<1. However, this does not mean that these 2 ground terminals at Koror Island can support EUVE requirements. In fact, they cannot. LEO4CAST simulation assumes that each mission needs to be supported by only one terminal and treats each ground station completely independently of the others. However, when there are multiple ground terminals required to support one mission, the minimum and maximum time between contacts and the ground terminal longitude separation requirements have to be considered (they are discussed in Chapter 4 and Chapter 5). As a general rule of thumb, in the LEONET performance analysis, 2 ground receiving terminals at 2 ground stations (same latitude but evenly separated in longitude) are more efficient than two ground terminals being located at the same ground station to support mission downlink. More analysis on ground station longitude effects is shown in Section 5.3.

3.3.2 LEO4CAST Mission Conflict Metrics

LEO4CAST applies the stochastic analysis approach and uses LEO missions' orbital information to generate LDC. The parameters and five main outputs in LDC are discussed here.

F a long term forecasting interval=1 day=24 hours[46]

B represents the probability, i.e., the percentage of F (one day), that one or more missions will be (simultaneously) visible to a specified ground site.

H the fraction of the total available contact time that is actually necessary to support the specified mission requirements.

$$H=B\times F$$

R_t $=B\times H$. This refers to the requested contact time as a percentage of F. R_t actually becomes the percentage of time per day that the ground site is requested to support these specified missions.

$$R_t=B\times H \text{ and } R_d=F\times R_t$$

L_t refers to the percentage of F (per day) that the specified missions cannot be supported by the ground site.

For all the LEO missions under study, B is calculated for each combination of LEO missions that is supported at each of the ground station locations. When only a single mission is considered, H is the same as Q for that mission supported at that ground station. For the case where all LEO missions are being viewed at the same time at this ground station (with a very low probability of occurrence), H represents the maximum mission contention level. It can be further interpreted as the minimum number of ground

[46] The actual forecasting interval makes no difference in LEO4CAST stochastic simulation results since most of the performance metrics are in percentages, as long as the simulation is **intended** for a long forecasting interval. It is more convenient to analyze the performance metric when a forecasting interval is considered to be a smallest interval unit: one day. Throughout the analysis, F refers to one day (24 Hours).

terminals needed at this particular ground station location (latitude) to support these missions without missions-to-mission conflict. If H>1, which means that the ground station load is greater than the ground station capacity, there will be lost data at this station. If H<1, all mission downlink requests can be supported with only one ground terminal, and there will be no subnet lost time and lost data due to mission-to-mission conflict. Thus lost time during the forecasting interval F (a day) is given by, L_t=B×(H-1). An example that illustrates these parameters is given in Section 3.4.

3.4 The use of LEO4CAST Output Metrics

One of the key network performance measurements is the subnet and network lost time percentage, where subnet refers to each ground station in LEONET.

L_s subnet lost time[47] percentage = ratio of the total subnet lost time to the total requested time in the subnet

L_n network lost time percentage = ratio of the total network lost time to the total requested time in the network

A perfect network should experience both zero L_s and zero L_n. An optimal network has the least L_n while satisfying other network constraints (usually, the cost specifications and reliability requirements). The political factors, ground site frequency interference, and other practical issues have not being considered in this analysis.

L_t should not be confused with L_s and L_n. L_t refers to the lost time as a fraction of the forecasting interval F (in this analysis, F=24 hours). L_s and L_n are defined as ratios of the insupportable time at a ground site to the total mission requested time, and they can be obtained from L_t and R_t. Because PPC is included as part of the required contact time during the LEO4CAST simulation, the real required mission contact time is given by Equation 7.

$$N_d \times R_p = (\sum R_t) \times F - N_d \times PPC \quad \textbf{Eq. 7}$$

[47] The lost time refers to the number of minutes during which a spacecraft is downloading data to ground stations but ground stations cannot receive it either due to conflict passes or equipment failure. The data downloaded by the spacecraft is lost. This happens if more than one satellite is passing through a ground station's view area at the same time.

Thus, the portion of lost time due to the real required mission contact time, not due to PPC, can be obtained as a fraction of the total lost time, as shown in Equation 8.

$$(\sum L_t) \times F \times (\frac{N_d \times R_p}{(\sum R_t) \times F}) \qquad \textbf{Eq. 8}$$

Substituting Equation 7 into Equation 8, and using the definition of the subnet lost time percentage, L_s can be obtained and simplified as shown in Equation 9.

$$L_s = \frac{(\sum L_t) \times F \times \frac{(\sum R_t) \times F - N_d \times PPC}{(\sum R_t) \times F}}{(\sum R_t) \times F - N_d \times PPC} = \frac{(\sum L_t) \times F}{(\sum R_t) \times F} = \frac{\sum L_t}{\sum R_t} = L_s \qquad \textbf{Eq. 9}$$

In Equation 9, $\sum L_t$ is the sum of the subnet lost time as a fraction of one day due to mission-to-mission conflict. $\sum R_t$ is the sum of the total required contact time as a fraction of one day. Usually it is NOT true that $L_n = \sum L_s$ because each subnet experiences different mission load $\sum R_t$. Instead, L_n should be calculated by Equation 10,

$$L_n = \frac{\sum(\sum L_t)}{\sum(\sum R_t)} \qquad \textbf{Eq. 10}$$

where $\sum\sum L_t$ is the total percentage of lost time as a fraction of one day for all subnets, and $\sum\sum R_t$ is the total percentage of requested contact time as a fraction of one day for all subnets. L_n is then the ratio of the total network lost time to the total network required contact time.

	B	H	Rt=BxH	Lt=Bx(H-1)	Missions
	7.51E-05	1.32452	9.95E-05	2.44E-05	SAMPEX+TOMSEP+FAST+SWAS+IRTS
	9.47E-04	1.25517	1.19E-03	2.42E-04	TOMSEP+FAST+SWAS+IRTS
	6.17E-04	1.18373	7.30E-04	1.13E-04	SAMPEX+FAST+SWAS+IRTS
	7.78E-03	1.11438	8.67E-03	8.90E-04	FAST+SWAS+IRTS
	3.20E-04	1.09446	3.50E-04	3.02E-05	SAMPEX+TOMSEP+SWAS+IRTS
	4.03E-03	1.02511	4.14E-03	1.01E-04	TOMSEP+SWAS+IRTS
			8.55E+00	0.00E+00	All Other Mission Combinations
Total			8.56E+00	1.40E-03	
Lost Time%			0.016%		

Table 12: Sample .csv file output used to generate subnet lost time percentage.

The following example illustrates the calculation of the subnet lost time percentage from a LEO4CAST LDC file. The example is for the case where 1/3 of the HIA load is applied to Thule, Greenland (76°, 69°). Table 12 shows a simplified output LDC file in which only the combinations that result in non-zero lost time are listed. Using the definition specified above, it is found that R_d=8.56%×24hrs×60min/hr=123.3min. The total lost time due to mission-to-mission conflict =0.0014%×24hrs×60min/hr=0.02min. Thus, L_s=0.02/123.3=0.016%.

3.5 Marginal Lost Time

Marginal lost time for a mission is the lost time due to mission-to-mission conflict when this mission is supported as the marginal mission to the baseline mission set. Marginal lost time percentage is the ratio of marginal lost time to the requested mission contact time. It is not the same as L_s, for which all missions are included in the baseline mission set and considered equally. However, there is a correlation between L_s and the average mission marginal lost time percentage. The higher the average marginal lost time percentage, the higher the L_s.

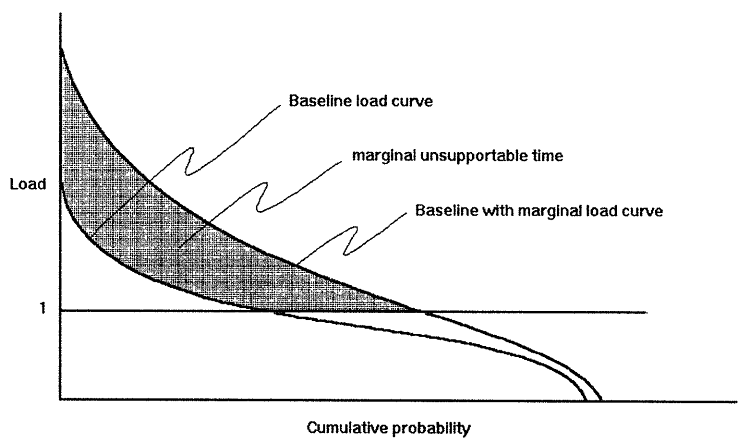

Figure 9: Load Duration Curve, network lost time, and marginal lost time.

Numerical integration is used on LDC to calculate the total increase of lost time due to the marginal mission load. Figure 9 illustrates the marginal lost time graphically using LDC. While the shaded area refers to the marginal lost time for this mission, the area above 1 but under the baseline-load-curve is the baseline subnet lost time for the baseline mission set. The intersection between the load duration curve and the vertical axis (load) indicates the maximum contention level at this subnet for supporting these missions.

When the control of the network is performed by a central processor, an algorithm is required to allocate the mission load distribution and schedule passes to maximize network performance, automatically and optimally. In this batch processing mode, the marginal lost time percentage would not be as important a figure as L_n. However, there might be the need for the network to support missions on a first-come-first-serve basis. In this decentralized mode, each subnet supports missions with a precedence of spacecraft appearances, in which case, marginal lost time would be more relevant to the average network lost time than L_n. A third scenario of the network control might be a centralized control with "user overwrite privilege." Though the scheduling algorithm can incorporate mission priority into the scheduling process, it might be important for each PI to be able to manually alter the schedules of downlink passes. In this scenario, both the marginal lost time and L_n would be important to the analysis of the average network lost time.

Detailed analysis of whether the centralized or decentralized control system is better for LEONET is beyond the scope of this project, but it is certainly one of the aspects of LEONET that needs to be addressed. We briefly compare the two different control systems here. A centralized network will have numerous advantages over a decentralized network for LEONET. Since an automated LEO-D type ground terminal can be remotely controlled within the network, command and data transmission are performed on a much larger time scale, and they are not constrained by the bottleneck of the terrestrial communication network system (ISDN). It is not necessary to use an extremely high data rate for the data transmission on the ground. A distributed network usually has the advantage of fast reaction time. A centralized network has the advantages of reliability, efficiency, and less control complexity. Because the scheduling process can be performed days ahead of the actual downlink passes, and because the data received by the ground terminal can be stored on hard disks before being distributed to PIs, "fast reaction" would be overkill. On the other hand, a centralized network provides a better load distribution scheme for LEO missions and improves overall network performance.

Chapter 4 Analysis Approach

There is no closed-form solution to this network performance optimization problem. As a result, a heuristic analysis approach is required. Furthermore, the possible combinations of quantity and locations of ground terminals that can be considered for the network are almost infinite. It is unrealistic to simulate each and every individual combination during the analysis. Practical constraints are used to reduce the problem to a manageable size. The potential ground station locations are limited to GSFC's list of 45 potential ground sites plus a few other popular ground locations within the continental United States.

Network tradeoff analysis cannot be performed without considering the performance requirement. In this analysis, network lost time percentage is desired to be less than 5%, which can be consequently translated into a 95% scientific data return rate. Furthermore, this optimization analysis only focuses on the lost time due to insufficient network capacity, not including the lost time caused by other factors, such as expected network down time due to system failure.

The solution to LEONET optimization is very sensitive to mission orbit and requirements. Hence it is the objective to obtain and demonstrate this procedure as a generic analysis approach so that this network ground station location optimization procedure can be applied not only to these 10 LEO missions, but also to any given set of one or more current and future LEO missions. This chapter describes this procedure and the generic analysis approach.

4.1 Network Performance and Mission Requirement

One cannot perform network tradeoff analysis without knowing network performance requirements. Nor can one optimize a network performance without considering network demands. Specifically, the LEONET ground station load condition and mission-to-mission conflict level cannot be analyzed without a knowledge of mission orbit and telemetry downlink requirements. The amount of data generated by a spacecraft that has to be delivered to ground stations, the telemetry downlink data rate, the spacecraft on-board solid state memory size or tape recorder capacity, and the allowable network lost time percentage are all important parameters for the LEONET ground station optimization.

Allowable Network Lost Time Percentage

For the time being, there is no specific figure from either DSN or NASA specifying the maximum allowable network lost time percentage for supporting a set of missions. Without a specific desired level of network performance, network tradeoff analysis becomes practically impossible. However, it is widely believed that, on average, near-Earth missions can lose up to 5% of total downlink telemetry data without affecting their major mission characteristics and objectives[48]. Nevertheless, this figure still varies from mission to mission. PIs may require 100% of data return during certain days of the mission phase and may not require any at other days. PIs and network managers usually work hand in hand to specify the mission support requirements, which may or may not vary on a daily basis. Spacecraft on-board instrument readout rate, total data volume, data downlink rate, mission priority, operational budget, mission objectives and required contact time, as well as ground station availability are all relevant parameters. Many of them can be negotiated such that the total scientific data return rate can be maintained at a fixed level. For example, a different telemetry downlink data rate can be selected to accommodate either longer or shorter available ground station available contact time. Furthermore, the mission requirement needs to be modified with the changing equipment operation conditions. If an on-board storage device breaks down, the mission downlink requirement will consequently change.

Minimum and Maximum Contact Time Per Pass

The minimum contact time per pass has a great impact on ground site selection and network performance. Generally, the longer the minimum contact time per pass, the more

[48] This subject has been discussed with many JPL staff , including Mr. Franz Borncamp from DSN Operations Office at JPL. They all agree on the 95% scientific data return rate requirement.

difficult it is to satisfy the mission requirement without losing any data. From the data acquisition point of view, the only physical constraint on the minimum contact time per pass is the time the receiver takes to lock onto the signal. This time is usually on the order of 10~30 seconds for a LEO-D type terminal, depending on the downlink frequency and the signal strength. However, there are geometric limitations at ground sites, such as land masks, that can limit the minimum elevation angle and consequently result in a shorter mission view periods and a maximum contact time per pass. When the maximum contact time per pass falls below the minimum requirement, that pass cannot be accepted as valid. Shorter minimum contact time per pass requires more passes to download the scientific data and consequently increases the complexity of scheduling downlink passes. Due to these constraints, DSN generally recommends a 6min or longer contact time per pass for LEO missions. For LEONET analysis, a conservative 8min minimum contact time per pass is used throughout the analysis.

Minimum and Maximum Time (Orbits) Between Contacts

Spacecraft on-board storage size and instrument readout rate have substantial influences on network performance. The storage size and the instrument readout rate ultimately determine both 1) the minimum amount of time (minimum number of orbits) it takes to fill up one storage buffer, and 2) the maximum amount of time (maximum number of orbits) it can store data without exceeding total on-board memory size. This is especially important for spacecraft with single storage devices. For example, SAMPEX requires two contacts per day at 12 hours apart and XTE requires one downlink contact for every 4 orbits during its extended mission phase. The minimum and maximum time between contacts have strong influences on ground station allocation. If the data stored in memory can be downloaded to a ground station in one pass, or if one mission such as EUVE requires more passes than one ground station can provide, locating two ground terminals at the same ground station does not help in terms of receiving downlink data. Thus, two ground terminals at the same location are not as efficient a setup as two ground terminals located at two stations (with the same latitude but separated evenly in longitude). More detailed information on determining longitudes of ground sites is discussed in Section 5.3.2.

The required number of passes and the contact time per pass for mission telemetry downlink depend on PIs' requirements as well as the ground station availability. A mission's required contact time varies with spacecraft on-board storage capacity and the available data rate. Furthermore, assuming a fixed downlink data rate is adapted by the spacecraft, the shorter the contact time per pass, the more passes are required for spacecraft to deliver data to the ground.

Pre- Post- Calibration Time (PPC)

Besides the required mission minimum contact time per pass, the required number of passes, and minimum and maximum orbits between downlink contacts, ground station's PPC also affects network performance. PPC includes the time to slew the antenna to desired position to receive spacecraft signal, the time for receiver initialization, as well as the time for an operator to reconfigure the station receiving mode. During the pre- and post- calibration period, the receiver cannot support other missions. Hence, PPC affects Q for each mission as well as L_n. Usually at a ground station, the smaller the PPC, the smaller the Q, and the better the network performance. The larger the aperture, the longer it takes to slew the antenna, and hence the longer the PPC. The DSN 26m antenna subnet currently requires 60min PPC. It is proposed that it be reduced to 12min by June, 1995. Because of the small aperture and light-weight antenna of the LEO-D type terminal, as well as autonomous tracking and receiving systems, LEO-D terminal's PPC is less than 1min. As a result, a 1min PPC is assumed for LEO-D type terminals for the analysis.

Because of the PPC requirement, three 20min passes (3×20) are not the same as 6×10 in the mission requirement analysis, even though the actual downlink contact time is the same from the spacecraft point of view. The 6×10 requirement has three more passes than the 3×20 requirement which results in a 3×PPC more total required contact time. However, since PPC is only 1min in this analysis, breaking 3 passes into 6 shorter passes has a minimal effect on the network performance.

Load Distribution Scheme

During the stochastic mission analysis, the expected mission view periods over a long forecasting interval have been used to analyze the mission-to-mission conflict level at a ground station. Similarly, the load at a ground station can also be viewed as a long term average load over a long forecasting interval. A pass for a mission can be subsequently divided into several fractions of passes which can be supported at several ground stations. One actual physical pass cannot be broken into two half passes, but it can be justified as long as the simulation is intended for a long forecasting interval. For example, a 1.5 passes per day requirement at a ground site can be interpreted as 3 passes for every two days. It can be further interpreted as 2 passes for the first day at this ground station, 1 pass for the next day, 2 passes for the day after, so on and so forth.

We have covered all the ingredients of LEONET analysis, from simulation tool LEO4CAST to mission and network performance requirements. Now we can introduce the LEONET analysis procedure.

4.2 Analysis Procedure

One problem associated with the LEONET optimization process is the interdependent relationship between the optimization of ground station location and that of the network load distribution scheme. The ground station location and load distribution scheme are two important aspects of the network. With a set of fixed ground sites, improving the network load distribution scheme improves network performance. Hence, network terminal location optimization cannot be achieved without network load distribution optimization. On the other hand, with a fixed load distribution scheme, improving ground terminal location improves network performance as well. Hence network load distribution optimization cannot be achieved without knowing the network capacity, which in turn depends on the quantity and locations of ground terminals. The consequence of this interdependent relationship is a circular loop in the network performance optimization. To avoid being trapped in a local minimal stable solution, heuristic analysis simulations should be run for a different set of starting points to observe if the solutions for different starting points converge [13]. Inner and outer iteration loops are adopted to perform perturbation and to locate an optimal solution.

The ground station location and load distribution scheme optimization processes are directly connected with the network forecasting and scheduling optimization where the similar circular loop can also be observed. Network capacity forecasting involves optimal ground resource allocation. Optimal network configuration cannot be achieved without optimizing the scheduling process. On the other hand, the optimal scheduling algorithm varies with ground terminal locations. The circular loop exists in almost every communication network optimization process but appears in different forms.

Furthermore, there are an infinite possible combinations of quantity and locations of ground terminals that can be considered for the simulation. With the heuristic approach, the simulation process becomes extremely cumbersome and time consuming. Instead of mindlessly going through each and every possible combination of ground terminal locations, practical constraints are used to simplify and reduce the complexity of the problem. The ground sites used for the simulation mainly come from the list of 45 potential sites suggested by GSFC, dated 4/26/90 [14]. These sites have at least some levels of established NASA infrastructure. There might be other non-NASA ground sites that theoretically provide better coverage for the network, but without the established NASA infrastructure, the ground site preparation and operation cost may be larger. Some popular ground sites within the continental United States, as well as some other established ground station locations, are also added to the list. However, political, economical, transportation, and climatic factors, as well as the ground site frequency band interference, are not considered.

The proposed network performance analysis procedure can be summarized in the 8-step analysis shown below, from which higher orders of ground station locations for supporting these missions can be determined [13].

☞ *Step 1.* From ground station location quality factor Q for each mission, select a set of ground stations to support these 10 missions. Select a load distribution scheme. Measure the subnet and network lost time percentage.

☞ *Step 2.* Perturb the ground station locations. Simulate and measure subnet and network lost time percentage for this perturbed network.

☞ *Step 3.* If the current subnet and network lost time percentage are not improved when compared with the original ones, stay with the original network configuration and go to step 5.

☞ *Step 4.* Observe the cost, i.e., the number of ground terminals in the network. If the perturbed network is not as cost effective (considering network performance per network cost) as the original one, stay with the original configuration and go back to step 5.

☞ *Step 5.* If there have been major improvements in last several perturbations, and it is possible to improve the network performance through more iterations, go to step 2.

☞ *Step 6.* With the obtained ground station locations, perturb the network load distribution scheme. If the performance improves, go to step 7.

☞ *Step 7.* If there have been major improvements in the last several perturbations, and it is possible to improve the network performance through more iterations, go to step 8.

☞ *Step 8.* If the new network analysis starting points (local minimum and maximum of ground station locations as well as the load distribution scheme) differ greatly from the previous analysis starting points, go to step 2. Otherwise, the analysis is complete.

The entire 8-step analysis procedure can be illustrated and visualized with the flowchart shown in Figure 10.

The analysis procedure starts with the Q analysis using LEO4CAST, which determines the best latitude of ground station location for each individual mission as a function of ground station latitude. Since the smaller the Q, the smaller the possibility of experiencing mission-to-mission conflict at a ground station location, the ground station location with the least Q is the optimal one for supporting that mission. As a result, the first order of ground station locations can be obtained. With Q for each mission, the 10 LEO missions are placed into subgroups according to the latitudes of their best supporting ground stations.

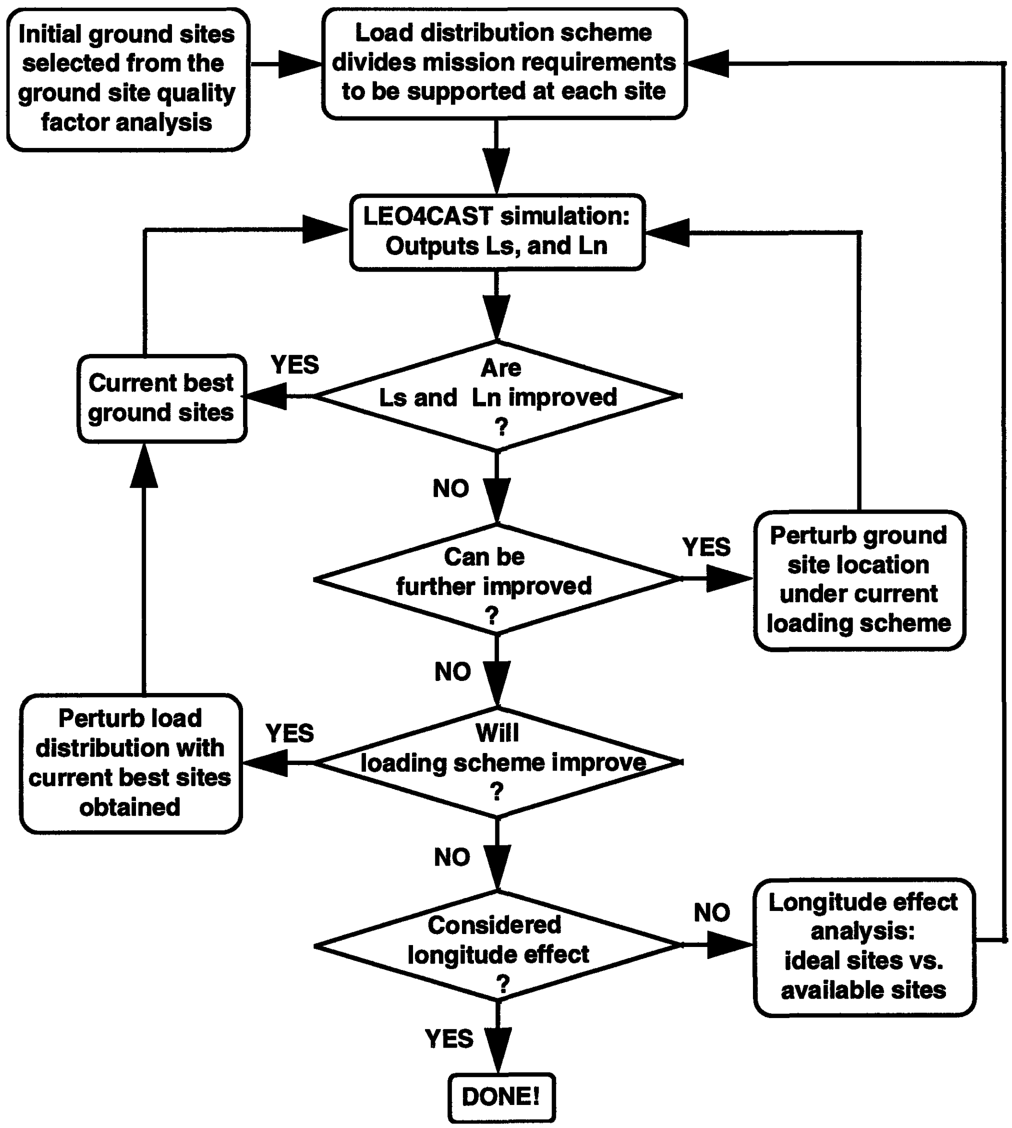

Figure 10: LEONET analysis flow chart.

An initial load distribution scheme is selected along with these ground station locations to start off the perturbation process. We obtain the subnet and network lost time percentage from the intermediate results produced by LEO4CAST simulation. To avoid being trapped into a local minimum or maximum, we perturb this network configuration by changing one of the system parameters. The perturbed set of starting points are used as the new set of analysis starting points for the next iteration of simulation. The subnet and network lost time percentage and network cost (which is reflected by the quantity of network ground terminals) are monitored through the perturbation. Thus, if network performance is NOT improving dramatically through many perturbation processes, it means that the lost time percentage and number of ground terminals has converged to a local or possibly a global minimum, where second order ground station locations are obtained.

With this locally stable solution, network load distribution scheme perturbation is carried out. Network lost time percentage is monitored during this perturbation to obtain the optimal load distribution scheme for the current set of network ground terminal locations. Through iterations and perturbation, as well as applying more practical constraints, the third order ground station locations are obtained.

Finally, the procedure incorporates ground site longitude effects into the analysis. The longitude separations of the obtained ground station locations are compared with the ideal ground station longitude separations. After considering the longitude effects, and possibly obtaining a new set of ground station locations as the new starting points, the procedure then performs the 8-step analysis again and reevaluates network performance with the new longitude information to obtain the third order ground station locations.

Chapter 5 LEONET Analysis Results

5.1 Preliminary LEONET Performance Estimate

The first analysis case is constructed to investigate the relationship between the network lost time percentage L_n and the number of ground terminals used to support these 10 missions at a given ground station. Trinidad (10°, 62°) is selected as the ground station location for this analysis case because it can support LIA, MIA, and also HIA missions. L_n is computed for 6 different scenarios, where the number of ground terminals used at Trinidad increases from 1 to 6. The simulation results are plotted in Figure 11. As expected, L_n and the number of ground terminals is inversely proportional.

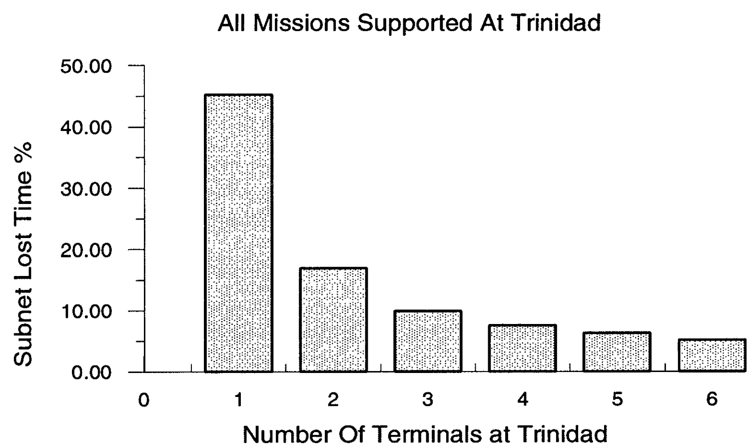

Figure 11: All 10 LEO missions supported Trinidad.

At Trinidad, with only 1 terminal to support all 10 LEO missions, L_n is 45.25%. With 5 terminals, L_n drops to 6.29%. The sixth terminal added into the network only reduces L_n to 5.13%. Figure 11 shows the important relationship between the lost time and the number of ground terminals in the network. The higher percentage of spacecraft scientific data return rate is associated with the higher cost of constructing, maintaining, and operating more ground terminal in LEONET. Since network tradeoff is governed by diminishing marginal return, marginal performance improvement per network cost decreases with network performance itself. 21 terminals are needed to support all missions at Trinidad with zero mission-to-mission conflict[49] and 100% scientific data return.

In the particular LEONET configuration shown above, the geometric advantages of ground station locations are not fully utilized. High latitude ground stations are more efficient than low latitude ground stations in supporting HIA missions because the former provide them better coverage. Similarly, low latitude sites are better than high latitude ground stations in supporting LIA missions. Improvements in L_s are expected when a high latitude ground station rather than Trinidad is used to support HIA missions.

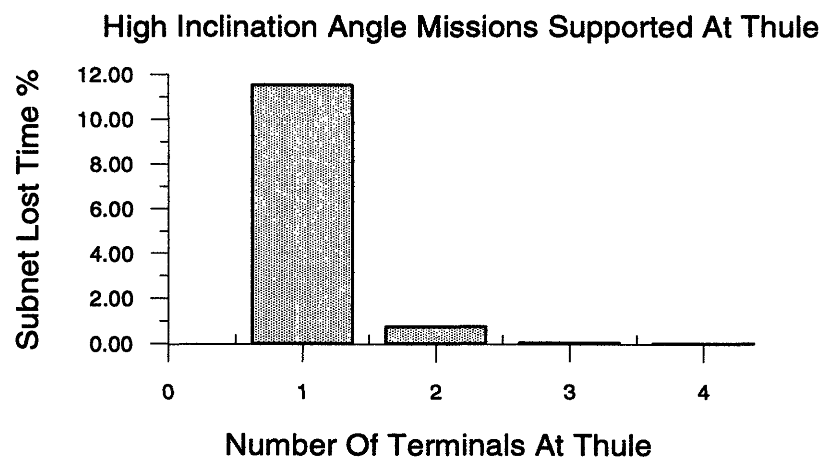

Figure 12: 5 HIA and MIA LEO missions supported at Thule.

As a result, for the following two analysis cases, 10 LEO missions are placed into two groups according to their inclination angles. The first group includes 5 LIA missions, and the second one includes 5 HIA and MIA missions. The high latitude ground station selected to support these 5 HIA and MIA missions is Thule, Greenland (76°, 69°), whose L_s is summarized in Figure 12.

[49] One probably is wondering why the network needs 21 terminals to avoid mission-to-mission conflict to support 10 LEO missions. This is because the simulation treats the view periods at one ground station completely independent of that at other ground stations in the network. Some missions, such as EUVE, require more than one terminal to support their telemetry downlink, and these multiple ground terminals are accumulated in the simulation. "Zero mission contention" probably is not an entirely accurate phrase to describe this situation. But since the phrase originates from LEO4CAST, it is kept and used in this report. One should be careful when interpreting the result.

L_s is 11.52% if only 1 terminal is utilized at Thule. L_s drops to 0.75% with 2 terminals and 0.016% with 3 terminals. All 5 HIA LEO missions can be supported with zero mission-to-mission conflict and 100% scientific data return if 4 terminals are used at Thule. This is consistent with the 3.97 maximum mission contention level observed in the LDC file for this analysis case.

A similar analysis is performed for the case where 5 LIA LEO missions are supported at Trinidad. Figure 13 shows the number of terminals at Trinidad and their associated L_s.

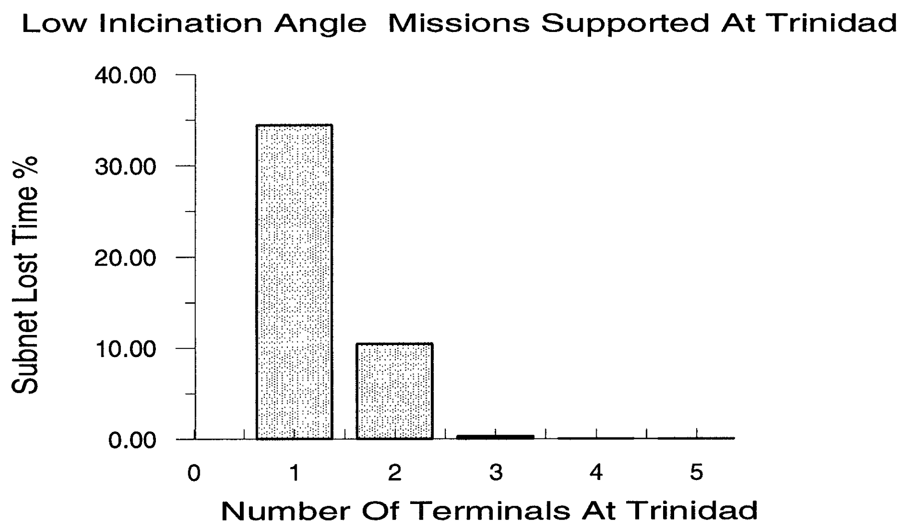

Figure 13: 5 LIA LEO missions supported at Trinidad.

In Figure 13, L_s is 34.47% when only 1 terminal is used at Trinidad. With 2 terminals, L_s decreases to 10.46%. L_s drops to 0.29% with 3 terminals and to 0.0049% with 4 terminals. 5 ground terminals are necessary to support these 5 LIA missions without any mission-to-mission conflict.

In the above two analysis cases, the total number of terminals in the network used to support all 10 LEO missions with zero mission-to-mission conflict and 100% scientific data return is 4+5=9 terminals. This is less than half of the 21 terminal result obtained from the very first analysis case, where all 10 LEO missions are supported at Trinidad. It indicates that a high latitude ground station is more efficient than a low latitude one to support HIA missions. By utilizing different latitudes for ground stations for different missions, the network performance can be improved dramatically. L_n for this LEONET configuration can be calculated from L_s using the relationship given by Equation 10 in Section 3.4. Both L_s and L_n are zero if 9 ground terminals (4 at Thule and 5 at Trinidad) are utilized in LEONET.

Suppose now we constrain the network to a total of only 5 ground terminals with 3 terminals at Trinidad and 2 terminals at Thule. Using L_s for the 2 terminal case from Figure 12, and L_s for the 3 terminal case from Figure 13,

$$L_n = \frac{((0.29\% \times 201) + (0.75\% \times 370))}{(201 + 370)} \times 100\% = 0.59\%,$$

where 201 and 307 are the total required contact times in minutes for LIA missions and HIA+MIA missions, respectively, including PPC. The total required contact time is governed by Equation 9 given in Section 3.3.2. Specifically,

$$\mathbf{R_t \times F = R_t} \times (24\text{hrs}) \times (60\text{min/hr}).$$

Similarly, if there were a total of 4 terminals in the network, 2 at Trinidad and 2 at Thule,

$$L_n = \frac{((10.46\% \times 201) + (0.75\% \times 370))}{(201 + 370)} \times 100\% = 4.17\%.$$

With a total of 3 terminals in the network, 2 at Trinidad and 1 at Thule,

$$L_n = \frac{((10.46\% \times 201) + (11.52\% \times 370))}{(201 + 370)} \times 100\% = 11.15\%.$$

With 3 terminals in the network, but 1 terminal at Trinidad and 2 terminals at Thule,

$$L_n = \frac{((34.47\% \times 201) + (0.75\% \times 370))}{(201 + 370)} \times 100\% = 12.62\%.$$

Suppose there were only 2 terminals in the network, the minimum number of terminals needed to support LEO missions in this network configuration (1 terminal at Trinidad and 1 terminal at Thule),

$$L_n = \frac{((34.47\% \times 201) + (11.52\% \times 370))}{(201 + 370)} \times 100\% = 19.60\%.$$

In this section we have shown the preliminary estimate for network performance without particularly optimizing ground station locations or network load distribution schemes. We observe that the network performance varies dramatically with the number of ground terminals in the network. In the next two sections, we will see how the network performance improves with better ground station locations and better load distribution schemes.

5.2 Ground Station Location Quality Factor Analysis

Due to unique orbit characteristics and mission requirements, each LEO mission has its own optimal terminal location for receiving telemetry downlink. Ground station location quality factor Q is used to determine the best terminal location for each individual LEO mission. At this stage of the analysis, network station location optimization is transformed into Q minimization. However, the ground stations with minimal Q will not necessarily guarantee an optimal network with the least L_n. L_n itself has to be used as the main performance metric in the iterative analysis process to ensure that optimal network ground station locations are obtained.

The Q factor for each mission at a ground location (latitude) depends on its orbit characteristics and mission requirements. The ground station longitude effect has been averaged out during the generation of expected view periods in LEO4CAST simulation. Hence, a station location is characterized by its latitude. However, the station longitude does affect the network performance, and it will be considered later in Section 5.3.2.

For a long forecasting interval, there is an inherent symmetry in the mission expected view periods between the northern and southern hemispheres of Earth. The northern hemisphere has geometric and infrastructure advantages over the southern hemisphere. As a result, Q for each LEO mission is simulated for twenty ground station locations with north latitudes varying from 0° to 90° at a 5° step size.

Figure 14 shows Q as a function of ground station latitude for each LIA mission. As discussed in Section 2.2, SASSE downlink requirements have been modified to 2×8 per day during the analysis. With the 8min minimum contact time per pass requirement, SASSE can only be supported at a ground station whose latitude is within 10°. For EUVE, GRO, and XTE, it is clearly shown that Q increases sharply when the ground station latitude approaches 35°.

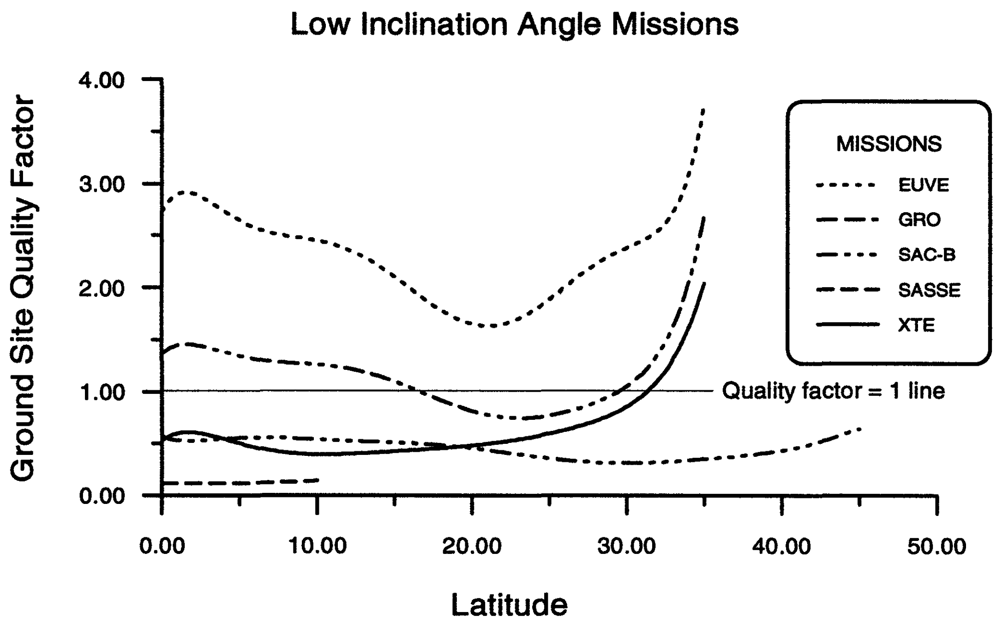

Figure 14: Ground site quality factor of 5 LIA LEO missions.

For GRO, SAC-B, SASSE, and XTE, the curves go under the Quality Factor = 1 line for some values of station latitudes. Each of these missions can be supported by only 1 terminal at these ground stations. Clearly, EUVE cannot be supported by only 1 ground terminal no matter where the terminal location is. 2 terminals are necessary and at least one of them has to have a latitude between 16° and 27°. Of course, if one terminal is located at a 20° latitude station, the other terminal can be located anywhere between 12° to 30°. This is because when multiple ground stations are used to support one mission, only the average Q for this mission is required to be less than 1.

The simulation result for HIA and MIA missions (except IRTS) is summarized in Figure 15. Q for IRTS as a function of ground station latitude is shown in Figure 16. As expected, the only MIA mission (SWAS) cannot be viewed if the ground station latitude is higher than 80°. However, 4 HIA missions prefer the station latitude to be 85° or higher.

As the ground station latitude gets higher, the extreme hostile weather, geographical limitations, transportation, and ground support issues come into consideration and make very high latitude stations quite undesirable. The potential site with the highest latitude, having at least some level of NASA infrastructure, is Thule. Thus, the 76° latitude of Thule is considered as the latitude limit for this analysis. At Thule, average Q for 5 HIA and MIA missions is 0.78.

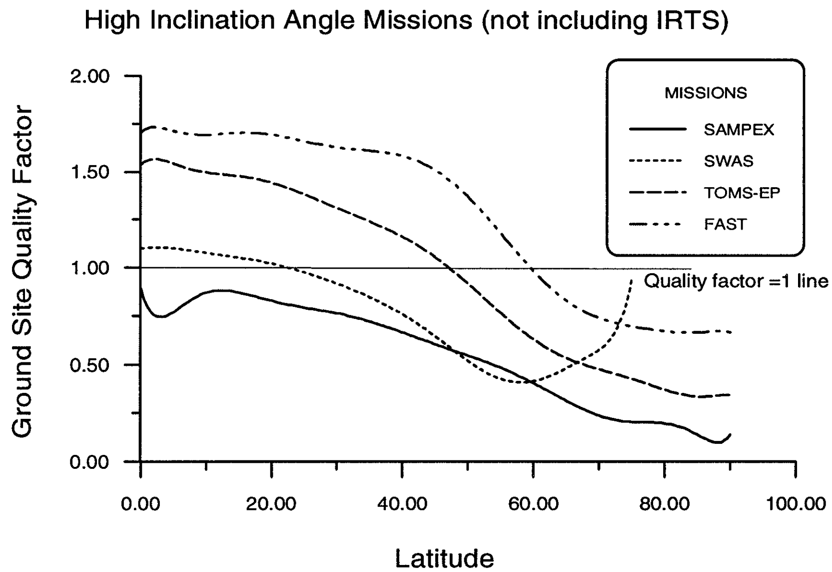

Figure 15: Ground site quality factor of 4 HIA LEO missions.

In Figure 15, all 4 missions have Q<1 at 76° latitude. Even though the average Q is less than 1, and each mission can be supported by 1 terminal with zero lost time percentage, this does not mean that all 4 missions can be supported by only 1 terminal at Thule with zero lost data. This is because the mission-to-mission conflict has not yet been considered.

Because of its high Q, IRTS is expected to cause most of the mission-to-mission conflict. In Figure 16, IRTS has quite a high Q for low latitude station locations. Q decreases as station latitude gets higher, but Q barely gets close to 1 (at 80° latitude).

The ground station latitudes with the least Q for each LEO mission are summarized in Table 13. For each individual LEO mission, the ground location with the least Q is the optimal terminal location to support that mission. From Table 13, the best terminal locations to support LEO mission telemetry downlink can be categorized into two major groups. For LIA missions, latitudes of stations[50] with the least Q vary from 5° to 30°; while for HIA and MIA missions, latitudes of stations with the least Q vary from 80° to 90°. This result is consistent with the preliminary analysis results found in Section 5.1.

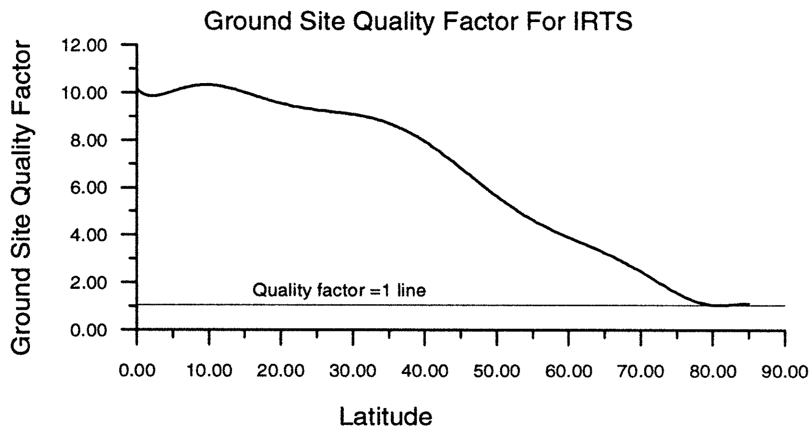

Figure 16: IRTS ground site quality factor level as a function of site latitude.

From Table 13, it can be observed that the LEO mission inclination angle has a strong correlation with the latitude of the ground station that has the least Q for that mission. The data are plotted in Figure 17.

MISSION	INCLINATION (deg)	LATITUDE (deg)
EUVE	28.45	20
FAST	83.00	85
GRO	28.50	25
IRTS	97.00	80
SAC-B	38.00	30
SAMPEX	82.00	90
SASSE	0.00	5
SWAS	65.00	55
TOMS-EP	99.28	85
XTE	23.00	10

Table 13: Mission inclination angle and best supporting site latitude.

[50] The ground site quality factor for SASSE is 0.131481 at 0° and 0.131089 at 5°. It is not expected that a 5° latitude site would have a better Q than a site on the Earth's equator to support SASSE. Even though 0° site has a better data margin and longer view periods, Q is expected to be the same. The minimal difference might be introduced by rounding off errors during LEO4CAST simulation.

Even though each mission has different orbit elements and mission requirements, it can be asserted, to a degree, that mission inclination angle has a linear relationship with latitude of station that has the least Q. As mission inclination angle increases, latitude of the station that best supports that mission also increases. This further verifies that LIA missions are better supported at low latitude ground stations, and HIA missions are better supported at high latitude ground stations.

After locating the best latitude of station locations for supporting each individual mission, the initial analysis starting points (ground terminal quantity and locations) can be subsequently obtained. Due to atmospheric drag and other secondary Solar-Lunar-Earth effects, for a long forecasting interval (from months to years), there is no correlation in mission orbit trajectories and expected view periods between all LEO missions. Thus, LEO missions can be considered independent of each other. As a result, the minimum of the sum of Q for each mission is equal to the sum of the minimum Q for each mission. Consequently, Q for each individual LEO mission can be superimposed to obtain the initial set of ground terminal locations for the perturbation analysis.

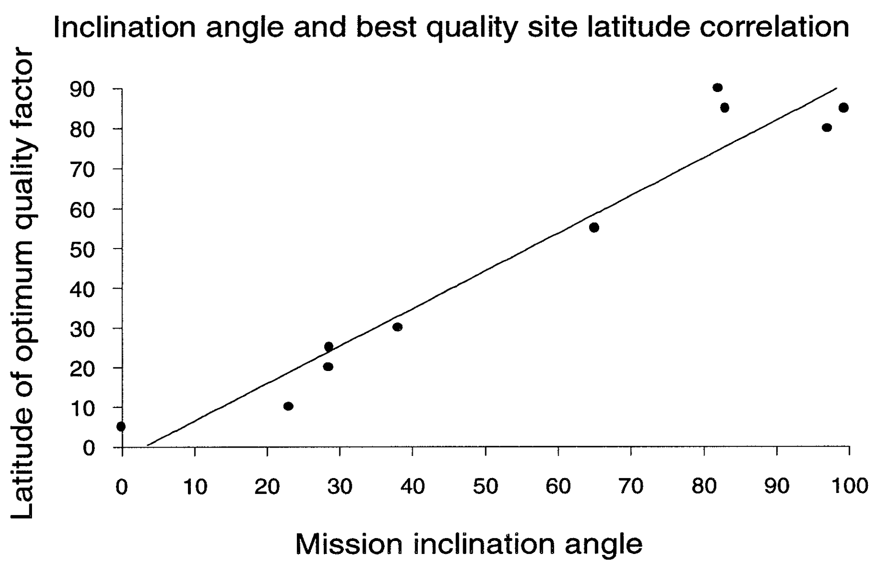

Figure 17: Mission inclination angle and best supporting site latitude.

From the Q factor curves shown in Figure 14, Figure 15, and Figure 16, these 10 LEO missions can be further categorized into 3 groups. A 10° latitude station is the best to support SASSE and XTE, and it yields an average Q of 0.27. A 20° latitude station is the best for EUVE, GRO, and SAC-B, yielding an average Q of 0.94. To support 5 HIA and MIA missions, a 75° latitude ground station is the best and yields an average Q of 0.79. Based on the ideal locations for the 3 groups, the initial 3 ground station locations for the 8-step perturbation analysis process are consequently obtained from the GSFC potential ground site list. They are Trinidad (10°, 62°), Maui, Hawaii (21°, 157°), and Thule, Greenland (76°, 69°).

5.3 Analysis Results

With the 8-step analysis approach introduced in Chapter 4 and the initial 3 ground station locations obtained from Section 5.2, simulations have been performed for various different combinations of ground station locations and network load distribution schemes. Other potential sites are used in the analysis for the perturbation process.

From the Q factor analysis, we know that only certain potential sites should be used to support these LEO missions. Thus, the potential ground station locations are further reduced to a smaller set which contains the following. Besides the 3 potential ground locations shown above, the others include Quito (0°, 78°), Kourou, French Guiana (5°, 53°), Guam (13°, 215°), Johnston Island (17°, 170°), Chiang Mai, Thailand (18°, 259°), Mexico City (19°, 99°), Honolulu, Hawaii (21°, 158°), Miami, Florida (26°, 80°), Las Palmas, Canary Islands (28°, 15°), Austin, Texas (30°, 98°), JPL (DSN), California (34°, 118°), and Fairbanks, Alaska (65°, 212°).

5.3.1 Perturbation Analysis Results

In Section 5.1, we learned that if 10 LEO missions are placed into 2 groups each having 5 LIA missions and 5 HIA+MIA missions, at least 2 ground terminals are needed (1 terminal at Trinidad and 1 at Thule) to have an L_n within 20% (19.60%). 3 terminals are necessary (2 at Trinidad and 1 at Thule) to have L_n within 12% (11.15%). Further ground terminal location perturbation and load distribution scheme perturbation analysis hopefully can improve the network performance following the analysis approach described in Chapter 4.

Many repeated simulations have been performed for this analysis. To illustrate how the final ground terminal locations and load distribution schemes are obtained, the 13 most significant analysis cases and their results are shown in this section.

For LIA missions, low latitude ground locations other than Trinidad are considered. From the Q factor analysis for each individual mission, Maui is found to be a better ground site than Trinidad for supporting EUVE, GRO, and SAC-B. SASSE, however, can only be viewed at stations with latitude $\leq 10°$ in order to satisfy the 8min minimum contact time per pass requirement. SASSE is an equatorial mission, and it has a pass for every orbit. Q for SASSE at any ground location with latitude $\leq 10°$ is roughly the same and very small. Hence it should be fairly easy to schedule SASSE downlink passes. When only 2 low latitude ground sites are considered in the network (Trinidad and Maui), SASSE can be solely supported at Trinidad. The rest of the LIA mission load can be evenly distributed between Maui and Trinidad.

2 ground terminals are necessary to support HIA and MIA missions at Thule with a 0.75% L_s (which is much better than the 5% network lost time percentage requirement). If there are 2 ground terminals at Thule, none of them can be utilized to support any LIA missions. This limits the possibilities of manipulating the load distribution schemes, which in turn, limits the possibilities for better overall network performance. On the other hand, if one of the two high latitude terminals is moved to a low latitude ground location, this terminal can support all LIA, MIA, and HIA missions. Hence there is more room with which to work to improve network load distribution schemes. Even though a low latitude ground station is not as efficient as a high latitude one to support HIA missions, this particular network configuration hopefully can improve the overall network performance. The downside of this configuration, as there always is in a tradeoff analysis, is the need for an efficient and complex scheduling algorithm.

Sample Analysis Case 1. Following the above reasoning, a new analysis case with 2 low latitude terminals and 1 high latitude terminal is considered. For the time being, we will consider a particular load distribution scheme that has 1/2 of HIA+MIA mission load be applied to Thule and the other 1/2 along with LIA mission load be applied to Trinidad and Maui (SASSE is solely supported at Trinidad). For this analysis case, L_s is 0.75% for Thule, 11.86% for Trinidad , and 7.09% for Maui, giving,

$$L_n = \frac{((7.09\% \times 184) + (11.86\% \times 202) + (0.75\% \times 185))}{(184 + 202 + 185)} \times 100\% = 6.72\%,$$

where 184, 202, and 185 are the total required contact times in minutes (including PPC) at Maui, Trinidad, and Thule respectively. With this particular network configuration and load distribution scheme, L_n decreased from the previous 11.15% of the 3 ground terminal analysis case illustrated in Section 5.1 to 6.72%.

Sample Analysis Case 2. From the Q factor analysis, it is assumed that Trinidad is a better site than Kourou Island to support LIA missions, including SASSE. A comparison is made between these two ground sites in terms of subnet lost time. The load distribution scheme for this comparison is to support SASSE, 1/2 of the other LIA mission load, and 1/4 of the HIA mission load with 1 ground terminal at each location. The simulation results are summarized in Table 14.

	Max Cont	Lost time%(day)	Subnet lost time%
Kourou	6.35	4.08	15.22
Trinidad	4.98	3.71	13.85

Table 14: Comparison between Kourou and Trinidad to support 1/2 LIA and 1/4 HIA load.

Trinidad is a better ground station location in terms of L_s with this load distribution scheme. Nevertheless, the difference between these two ground sites with this particular load distribution scheme is minimal. Will Trinidad rather than Kourou Island be the better station location for any other load distribution schemes as well?

	Max Cont	Lost time%(day)	Subnet lost time%
Kourou	5.22	1.40	13.24
Trinidad	5.02	1.21	10.18

Table 15: Comparison between Kourou and Trinidad to support 1/2 LIA and 1/6 HIA load.

Sample Analysis Case 3. Another comparison is made when these two sites are utilized to support SASSE, 1/6 of HIA mission load, and 1/2 of LIA mission load. The results are summarized in Table 15.

The difference in terms of L_s between these two sites becomes more significant than that with the load distribution scheme used in Sample Analysis Case 2. Trinidad has more than 3% less L_s than Kourou does. Neither Trinidad nor Kourou Island is a good station location to support HIA missions. By removing 1/3 of HIA mission load away from these two sites, both stations experience improvements in L_s. Furthermore, since Trinidad has a higher latitude than Kourou, it has better performance when used to support LIA missions (except for SASSE) which have 23°~38° inclination angles, and Trinidad is expected to improve more than Kourou Island does. The result is consistent with what is expected from the single mission ground site quality factor analysis. One implication that can be drawn from these analysis cases is that Trinidad is the optimal low latitude ground terminal location to support both SASSE and other 4 LIA missions.

Sample Analysis Case 4. Another variation for Sample Analysis Case 1 is to alter the load distribution scheme imposed on the 3 ground stations. In this analysis case, 2/3 of HIA+MIA mission load is applied to Thule, and the other 1/3 along with LIA mission load is applied to Maui and Trinidad (SASSE is supported at Trinidad). With this load distribution scheme, L_s is 3.01% at Thule, 10.18% at Trinidad, and 4.17% at Maui, resulting in a new level of network performance with L_n,

$$L_n = \frac{((4.17\% \times 153.17) + (10.18\% \times 171.17) + (3.01\% \times 246.67))}{(153.17 + 171.17 + 246.67)} \times 100\% = 5.47\%.$$

Sample Analysis Case 5. We have used Thule as the only high latitude station location. There is another high latitude site, Fairbanks, Alaska, considered for this analysis. How much more effective is Thule over Fairbanks in terms of L_s when used to support HIA+MIA missions? The simulation is performed for the following load distribution scheme. If 1/2 of HIA+MIA mission load is applied to each of these 2 ground sites, Thule is 10 times more effective than Fairbanks in terms of L_s as it is shown in Table 16.

	Max Cont	Lost time%(day)	Subnet lost time%
Fairbanks	2.68	1.00	7.78
Thule	1.99	0.10	0.75

Table 16: Comparison between Fairbanks and Thule to support 1/2 of HIA load.

The major contributor to the difference in performance between these two ground sites is mission IRTS. IRTS has a fairly low orbit apogee and perigee (400 km × 500 km). It results in shorter view periods at Earth ground stations (especially at low latitude ground stations) than missions with higher apogees and perigees. The lower the ground station latitude, the shorter the IRTS average view periods at that station. Consequently, it is harder to support IRTS 6×10 contact time at a low latitude ground station.

Sample Analysis Case 6. We now consider the case where Thule and Fairbanks each experiences 2/3 of HIA+MIA mission load. With this load distribution scheme, Thule is about three and a half times more efficient than Fairbanks. The simulation results are summarized in Table 17.

	Max Cont	Lost time%(day)	Subnet lost time%
Fairbanks	3.57	1.84	10.73
Thule	2.65	0.52	3.01

Table 17: Comparison between Fairbanks and Thule to support 2/3 HIA load.

As more mission load is applied to Thule and Fairbanks, both ground sites experience higher L_s. Furthermore, L_s of Thule is increasing at a faster rate than that of Fairbanks. The intuitive reason can be illustrated with the following two scenarios. If Thule is a better ground site than Fairbanks to support HIA and MIA missions, a load distribution scheme (very light load) must exist such that L_s at Thule is zero but L_s at Fairbanks is non-zero. Mathematically this implies that Thule has an infinitely better performance than Fairbanks. On the other hand, as mission load at both ground sites gets heavier, both of the ground stations will experience higher L_s. When the load gets extremely heavy such that L_s at each site approaches 100%, the performance for both ground sites can be considered the same.

Even though the latitude difference between Thule and Fairbanks is only 11°, the difference in performance can be very significant. Depending on the load conditions, Thule can be 3 to 10 times better than Fairbanks in terms of subnet performance. The edge of supporting HIA+MIA missions clearly always goes to a higher latitude station.

Sample Analysis Case 7. In this new analysis case, we consider the network with a total of 4 ground terminals (1 terminal is located at Thule and 3 terminals are located at 3 low latitude ground sites). The 3 low latitude sites selected in this analysis case are Maui, Guam, and Trinidad. 1/2 of HIA+MIA mission load is applied to Thule, while the other 1/2 is evenly distributed to these 3 low latitude stations. Each of the 3 low latitude stations supports 1/6 HIA+MIA mission load, and also 1/3 LIA mission load. However, SASSE is only supported at Trinidad.

In this scenario, since 1 terminal at Thule is only supporting 1/2 of HIA+MIA mission load, L_s is expected to be the same as when 2 terminals are used to support all HIA+MIA mission load. And indeed L_s observed at Thule is 0.75%. Trinidad experiences a L_s of 4.19%, while Guam and Maui each experiences 4.08% and 3.81% L_s respectively. The overall network performance is given by,

$$L_n = \frac{((4.08\% \times 122.67) + (3.81\% \times 122.67) + (4.19\% \times 140.67) + (0.75\% \times 185))}{(122.67 + 122.67 + 140.67 + 185)} = 2.97\%.$$

The network performance as a whole has improved from L_n=4.17% from the 4 terminal (2 at Thule and 2 at Trinidad) network case shown in Section 5.1 to L_n=2.97%.

	Latitude	Max Cont	Lost time%(day)	Subnet lost time%
Quito	0	4.28	0.433	5.09
Kourou	5	4.25	0.426	5.00
Trinidad	10	4.1	0.397	4.66
Guam	13	3.90	0.348	4.08
Johnston Is.	17	3.72	0.328	3.85
Mexico City	19	3.59	0.326	3.82
Maui	21	3.52	0.324	3.81
Miami	26	3.62	0.330	3.88
Las Palmas	28	3.65	0.310	3.64
Austin	30	3.85	0.345	4.05
JPL	34	4.63	0.658	7.73

Table 18: Comparison between 11 sites to support 1/3 LIA (no SASSE) and 1/6 HIA load.

Sample Analysis Case 8. Guam is a good potential site for LEONET because of its moderate latitude as well as the established NASA infrastructure. However, its latitude is lower than either Johnston Island or Maui. Which site is more efficient and cost effective in terms of L_s for supporting LIA missions? With this question in mind, a comparison is made for 11 low latitude potential sites considered in the analysis. The simulation is performed for the case where each station supports 1/6 HIA+MIA mission load and 1/3 LIA mission load (no SASSE). The results are summarized in Table 18.

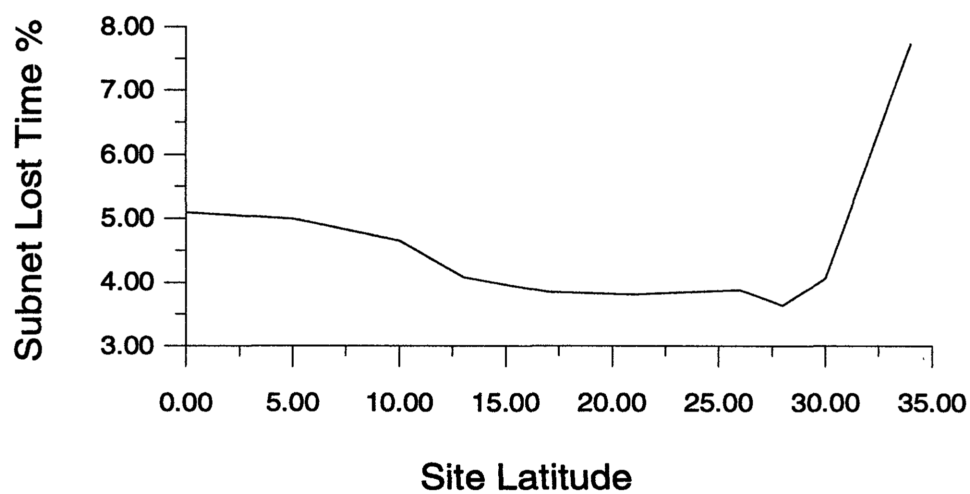

Figure 18: Subnet lost time percentage as a function of site latitude for analysis case 8.

The results closely match expectations except for one ground site, Las Palmas, which seems to have the best performance among all 11 sites. The discrepancy between L_s simulation and the Q factor analysis results is discussed later in Section 5.4.2. Figure 18 shows L_s as a function of ground station latitude for this particular load distribution scheme. We observe from the plot that terminal locations with latitudes between 15° to 28° best support LIA missions. Maui and Johnston Island are not much different in terms of L_s. However, both sites have noticeable advantages over JPL, which has the same latitude as DSN at Gold Stone (34°, 116°). Guam may not be the best ground terminal location in terms of L_s to support LIA missions. However, it may be more cost effective (performance over total subnet cost) than many other ground sites because of its terrestrial communication, weather, political environment, and security advantages.

Sample Analysis Case 9. SAMPEX requires little contact time, and FAST has a highly elliptical orbit which gives relatively long view period duration. They both can be fairly easily supported at a low latitude ground station. Due to its low orbit apogee and rather long required contact time, IRTS causes the majority of the mission-to-mission conflict when it is supported at a low latitude station. To get around this problem, most of the IRTS requirements can be applied to a high latitude ground site, and hopefully the overall network performance can be improved. This analysis case is constructed for this purpose. There are 4 ground stations in the network (Thule, Trinidad, Guam, and Maui). The load distribution scheme is that Thule supports 2/3 of the IRTS load and 1/2 of the other HIA+MIA mission load. The other 1/3 of the IRTS load is evenly distributed between Guam and Maui. The rest of the mission loads are evenly distributed to Trinidad, Guam, and Maui. The resulted L_s are 2.36%, 0.62%, 3.81%, and 4.08% for Thule, Trinidad, Guam, and Maui respectively. Hence, the network L_n is,

$$L_n = \frac{((4.08\% \times 122.67) + (3.81\% \times 122.67) + (0.62\% \times 129.67) + (2.36\% \times 196))}{(122.67 + 122.67 + 129.67 + 196)} \times 100\% = 2.65\% .$$

Compared with the results in Sample Analysis Case 8, L_s at Thule has increased from 0.75% to 2.36% due to the extra 1/6=2/3-1/2 IRTS load. L_s at Trinidad improves from 4.19% to 0.62% because of the absence of the 1/6 IRTS load it previously supported. L_s at Maui and Guam stays the same since the total mission load that each ground terminal supports has not changed. However, the overall network performance improves. L_n drops to 2.65% from 2.97%. The improvement may not seem significant, but it verifies intuition. It is expected that moving 1/6 of a HIA mission load from a low latitude ground site to a high latitude one would improve network performance.

Sample Analysis Case 10. Sample Analysis Case 9 shows the unbalanced L_s between the 3 low latitude ground stations. Guam and Maui experience 6 times more L_s than Trinidad does. One reasonable and intuitive guess is that if there is a particular load distribution scheme that can make L_s for each ground site roughly the same, the overall network performance will improve. This analysis case is constructed to verify this hypothesis. To decrease L_s at Maui and Guam and increase L_s at Trinidad, 1/6 of EUVE (9×10 total mission requirement) load from both Guam and Maui (1/12 from each site) is moved to Trinidad. The simulation results are not as good as expected. L_s at Thule, Trinidad, Maui, and Guam are 2.36%, 8.07%, 4.07%, and 4.02% respectively, resulting in

$$L_n = \frac{((4.07\% \times 114.42) + (4.02\% \times 114.42) + (8.07\% \times 146.16) + (2.36\% \times 196))}{(114.42 + 114.42 + 146.16 + 196)} \times 100\% = 4.50\%.$$

The network performance did not improve with this particular load distribution scheme. L_n actually increases from 2.65% of Sample Analysis Case 9 to 4.50%. The problem is that 1/6 of EUVE load drives L_s at Trinidad from a previous 0.62% to 8.07%, twice as high as L_s at Maui and Guam. However, the failure of this particular distribution scheme does not imply that the idea behind this analysis case is wrong. It simply means that a better distribution scheme is desired to improve the network performance, as we will see in the next analysis case.

Sample Analysis Case 11. Another different load distribution scheme is used to try to "normalize" L_s at all 4 ground terminal locations. In this case, 1/9 of IRTS instead of EUVE load is moved from Maui and Guam (1/18 from each site) to Trinidad. The simulation results fall into expectation this time. L_s at Thule, Trinidad, Maui, and Guam are 2.36%, 1.62%, 0.84%, and 1.13% respectively. L_s at the 3 low latitude sites have all improved from those of Sample Analysis Case 10, and gives

$$L_n = \frac{((1.13\% \times 119) + (0.84\% \times 119) + (1.62\% \times 137) + (2.36\% \times 196))}{(119 + 119 + 137 + 196)} \times 100\% = 1.61\%.$$

The overall network performance improves from 2.65% of Sample Analysis Case 9 to 1.61%. It verifies the fact that a better load distribution scheme can improve network performance. It also supports the intuition shown in Sample Analysis Case 10. An optimal load distribution scheme is the one that makes each ground station experience the same L_s.

The above statement can be considered as the criterion for constructing the optimal scheduling algorithm. We can justify it a little more rigorously. Suppose there are 4 ground stations in the network, and the required contact time at each ground station is represented by variables A, B, C, and D respectively, where A, B, C, and D are positive numbers and A+B+C+D is a constant. Furthermore, each ground station has an L_s of α, β, χ, and δ, respectively, with $0 \le L_s \le 1$. And L_n can be obtained from Equation 11.

$$L_n = \frac{A*\alpha + B*\beta + C*\chi + D*\delta}{A+B+C+D} \qquad \textbf{Eq. 11}$$

To obtain an optimal load distribution scheme is to find the values of A, B, C, and D such that L_n is minimized in Equation 11. Since A+B+C+D is a constant, it is the goal to minimize $A*\alpha+B*\beta+C*\chi+D*\delta$.

It is necessary to specify the relationship between A, B, C, and D and α, β, χ, and δ before this minimization problem can be solved. Unfortunately, their complex and nonlinear relationship cannot be easily modeled. The exact relationship between them depends on mission requirements as well as ground station locations. However, since the 8-step optimization analysis only applies small perturbations to ground station locations during each iteration, A and α, B and β, C and χ, and D and δ can be modeled as if they have an incremental linear relationship, at least to the first degree. It is intuitive that, on average, more mission downlink requirements at a ground station result in more subnet lost time. Furthermore, it can be argued that the incremental linear coefficients are the same for each ground station. As a result, the following equations can be obtained: $A=\alpha \times a$, $B=\beta \times b$, $C=\chi \times c$, $D=\delta \times d$, where a=b=c=d are some constants that can be empirically obtained. Thus L_n can be expressed as it is shown in Equation 12.

$$L_n \approx \frac{a*\alpha^2 + b*\beta^2 + c*\chi^2 + d*\delta^2}{A+B+C+D} \qquad \textbf{Eq. 12}$$

Since A+B+C+D, and a=b=c=d are all constants, it can be easily proved that, for any A, B, C, and D, L_n is minimized if and only if $\alpha^2=\beta^2=\chi^2=\delta^2$. Furthermore, since all α, β, χ, and δ are between 0 and 1, L_n is minimized if and only if $\alpha=\beta=\chi=\delta$. As a result, an optimal load distribution scheme is to apply load A, B, C, and D, respectively, to each ground station such that $\alpha=\beta=\chi=\delta$ is true. A downlink scheduling algorithm can be constructed based on Equation 12.

Sample Analysis Case 12. From Sample Analysis Case 9, we found that Las Palmas is a "better" low latitude ground site to support LIA missions. The network performance is expected to improve subsequently if Las Palmas is used instead of Guam in Sample Analysis Case 11. This analysis case uses the same load distribution scheme as Sample Analysis Case 11 except that Guam is substituted by Las Palmas. While L_s at Thule, Trinidad, and Maui are the same as the ones from Sample Analysis Case 11, L_s at Las Palmas improves to 0.67% from 1.13% at Guam. Consequently, the overall network performance also improves with,

$$L_n = \frac{((0.67\% \times 119) + (0.84\% \times 119) + (1.62\% \times 137) + (2.36\% \times 196))}{(119 + 119 + 137 + 196)} \times 100\% = 1.51\%.$$

Sample Analysis Case 13. As described in Chapter 4, iterative simulations are performed in two different loops. To see which low latitude stations would be the most efficient in supporting LIA missions with the load distribution scheme shown in Sample Analysis Case 12, a comparison is made for the 11 low latitude sites under analysis. The results of the simulation are summarized in Table 19.

	Latitude	Max Cont	Lost time%(day)	Subnet lost time%
Quito	0	3.84	0.196	2.056
Kourou	5	3.81	0.185	1.946
Trinidad	10	3.68	0.154	1.624
Guam	13	3.37	0.093	1.13
Johnston Is.	17	3.19	0.073	0.88
Mexico City	19	3.05	0.071	0.86
Maui	21	2.99	0.070	0.84
Miami	26	3.09	0.075	0.91
Las Palmas	28	3.14	0.055	0.67
Austin	30	3.34	0.091	1.10
JPL	34	4.14	0.418	5.06

Table 19: Comparison between 11 ground sites for analysis case 13.

The first 3 ground locations (Quito, Kourou, and Trinidad) are compared under the same load distribution scheme that was used on Trinidad in Sample Analysis Case 11. The other 8 ground locations are compared with the load distribution scheme that was made for Las Palmas in Sample Analysis Case 12. The data are plotted in Figure 19. It is observed again that Las Palmas is the best ground site to support LEO missions with this particular load distribution scheme. From individual mission Q factor analysis, 20° seems to be the best ground station latitude to support LIA missions. However, with load distribution variation, as soon as HIA mission load is applied to low latitude stations, the latitude of best supporting ground stations also shifts. From the results shown in Figure 19, the best location to support missions with the current load distribution scheme is Las Palmas. Maui stands as the second best even though the difference in subnet performance between the two ground sites is minimal. Further explanations on the discrepancies are discussed in Section 5.4.2.

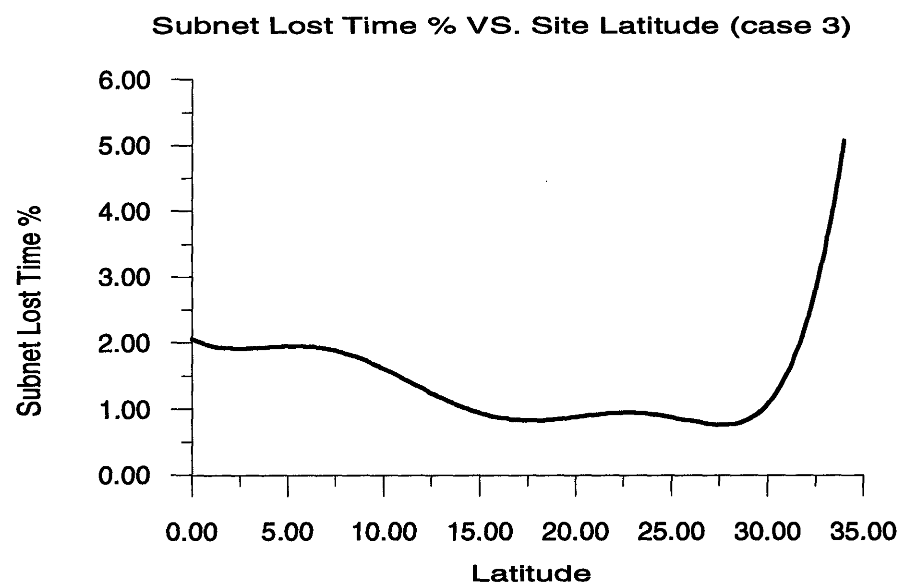

Figure 19: Subnet lost time percentage as a function of site latitude for analysis case 13.

One thing worth noting is that all the results obtained in the analysis are very mission requirements and mission orbits sensitive. The results only apply to the set of 10 LEO missions under study. For a different set of missions or even different mission requirements, the optimal locations obtained will be different. However, the approach and procedure taken in this analysis will remain the same and can be applied to any set of 1 or more current and future LEO mission.

5.3.2 Ground Site Longitude Effect

As aforementioned, in LEO4CAST simulation, ground stations are characterized only by their latitudes. The longitude effects of a ground site have been averaged out during the expected view periods calculation in LEO4CAST. One reasonable question to ask is that if Maui is more efficient than Guam in supporting LIA missions, why should not the 2 ground terminals both be placed at Maui, instead of 1 terminal at Guam and 1 at Maui?

First of all, as discussed in Section 4.1, some LEO missions, such as EUVE, require multiple ground terminals at multiple ground stations at different longitudes (possibly evenly separated) to support their telemetry downlink requirements. As a result, it is not efficient to place 2 ground terminals at 1 station. Moreover, the ground station longitude itself does not have much of an impact on network performance. It is the longitude separation between ground stations that really affects network performance. The ideal longitude separation between ground stations is determined by mission orbits, spacecraft on-board memory size, and remote-sensing instrument readout rate.

It is the most efficient way to locate ground stations such that they are evenly spaced in longitude. Allocating multiple terminals at one ground station is useful in dealing with mission-to-mission conflict at a ground station, but it does not help if this station cannot provide enough contact time for a single mission. This can be illustrated with the following example. EUVE has a 9×10 per day required contact time with a minimum of 8min contact time per pass. From LEO4CAST mission view period simulation, it is found that, on average, Maui, (the best ground site to support EUVE), experiences 6 EUVE passes per day that are longer than 8min. Suppose that there are 3 ground terminals located at Maui to support EUVE, and they can simultaneously receive telemetry data from EUVE. However, all 3 terminals experience exactly the same 6 available passes each day. 2 of the 3 terminals at Maui are redundant because the telemetry data received during these 6 passes are exactly the same. On the other hand, if 3 terminals are located at 3 different ground sites, which have the same latitude as Maui but are separated by 120° from each other in longitude, there will be no overlaps in view periods for each ground stations, i.e., each station sees 6 totally different passes each day. Thus, on average, there are a total of 3×6=18 available passes each day that are longer than 8min, all of which can be used to download EUVE telemetry data.

Furthermore, spacecraft may need several orbits to fill up their on-board storage buffer, which consequently specifies the minimum time between downlink contacts. The number of orbits needed (the minimum time between contacts) depends on spacecraft instrument readout rate and its memory size. For example, XTE requires 4 orbits to fill up its solid state memory. Especially for LIA missions, available passes at a ground station tend to appear in successive orbits that are about 95min apart. If a spacecraft downloads its telemetry data during its first pass to the ground station, the next several successive passes then are "wasted" because there is no more fresh scientific data to be delivered. Thus, allocating multiple terminals at one ground station does not increase the total telemetry data return.

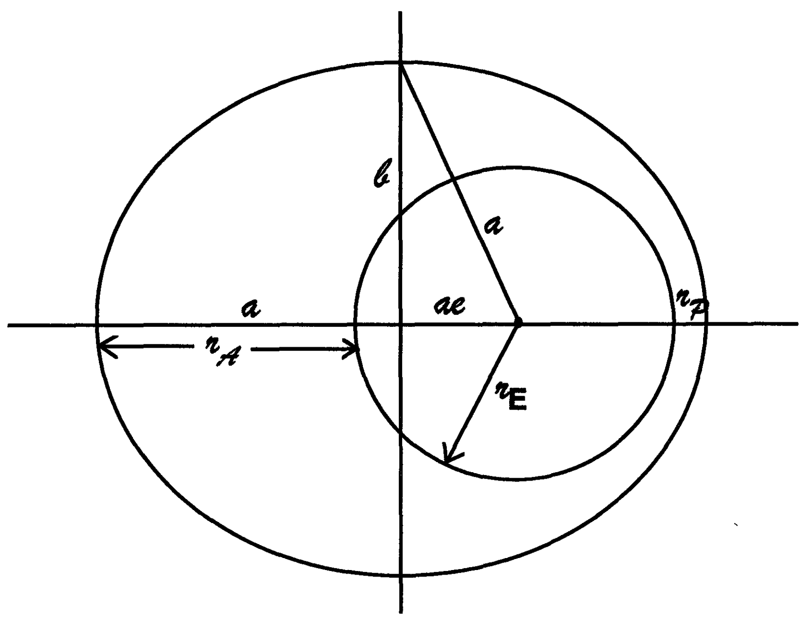

Figure 20: LEO mission elliptical orbit parameters.

Every time a satellite orbits Earth once, it results in certain longitude shifts (θ) due to the Earth's self-rotation (when the satellite crosses the same latitude after circling around Earth for one orbit). θ can be found as a function of mission orbit parameters. Figure 20 shows the elliptical orbits and their associated parameters. A circular orbit is just a special case of an elliptical orbit where the eccentricity becomes 0.

$\mathcal{P}_o$ is defined as the spacecraft orbit period in seconds and can be expressed in terms of a, the orbit semi-major axis, as shown in Equation 13,

$$\mathcal{P}_o = \frac{2\pi a^{3/2}}{\sqrt{\mu}} \qquad \textbf{Eq. 13}$$

where μ=398600.5km^3/sec^2 is the gravitational parameter, and it is the product of Earth mass (M) and gravitational constant (G). The orbit semi-major axis, a, can be obtained from, mission apogee (r_A), mission perigee (r_P), and Earth radius (r_E=6378.14km) [15] and is shown in Equation 14.

$$a = \frac{r_A + r_E}{(1+e)} = \frac{r_P + r_E}{(1-e)} \qquad \textbf{Eq. 14}$$

The eccentricity e in Equation 14 can also be obtained from r_A and r_P, and is given in Equation 15.

$$e = \frac{r_A - r_P}{r_A + r_P + 2r_E} \qquad \textbf{Eq. 15}$$

Ignoring second order effects, such as eastward and westward drift, to the first degree, θ can be expressed as a function of $\mathcal{P}_o$, and is shown in Equation 16.

$$\theta = \frac{\mathcal{P}_o(Sec.) \times 360^\circ}{24 \times 3600(Sec.)} \qquad \textbf{Eq. 16}$$

Thus, θ is only a function of mission apogee and perigee and it is independent of mission inclination angle. Table 20 lists the orbit semi-major axis, orbit period, and corresponding θ for each of the 10 LEO missions.

Since only 1 high latitude ground station is used to support partial HIA mission load, the station longitude itself makes no difference in network performance. It is the low latitude ground stations that need to be considered. The optimal ground station longitude separation depends on mission orbits and mission requirements. For non-deterministic LEO missions and over a long forecasting interval, on average, the ideal ground station longitude separation for 3 low latitude ground stations is 120°. From Table 20, it can be seen that for all missions (except for FAST), θ due to the Earth's self-rotation is ~24°. The number of orbits it takes to fill up the on-board memory varies from mission to mission and depends on mission instrument readout rate. But on average, it takes about 4 or 5 orbits. In this case, the longitude separation of low latitude ground stations should be either 24°×4=96° or 24°×5=120°. It matches with the ideal ground station longitude separation.

MISSION	Semi-major axis (a) (km)	Orbit period (P_o) (minutes)	Longitude shift per orbit (θ) (deg)
EUVE	6906.14	95.19	23.80
FAST	8653.14	133.51	33.38
GRO	6828.14	93.59	23.40
IRTS	6828.14	93.59	23.40
SAC-B	6928.14	95.65	23.91
SAMPEX	6981.14	96.75	24.19
SASSE	6882.14	94.70	23.68
SWAS	6978.14	96.69	24.17
TOMS-EP	7333.14	104.16	26.04
XTE	6978.14	96.69	24.17

Table 20: Longitude shift per orbit for 10 LEO missions.

However, the match between the station longitude separation and that obtained from the θ analysis is just a coincidence. At this stage, the task of allocating optimal ground terminals is transformed into pairing up ground stations obtained in Section 5.3.1 such that the station longitude separation can be as close to 120° as possible. If only 2 low latitude ground stations are utilized in the network, then ideally they should be 180° apart. However, there is nothing wrong with 2 terminals being separated by 120° in longitude since the number of orbits for a spacecraft to fill up a storage buffer is still approximately 4 or 5 orbits. The ground sites longitude separations for the 10 low latitude sites are listed in Table 21.

In Table 21, no combination of 3 ground sites exists that satisfies the exact 120° longitude separation specification. Neither are there any combinations of 2 ground terminals that satisfy the 180° longitude separation requirement. But there are several pairs of ground sites whose longitude separations are close to 120°. Maui can be paired up with Las Palmas, Kourou Island, and Trinidad. Johnston Island can be paired up with Las Palmas, Kourou Island, and Trinidad. Guam can be paired up with Quito, Miami, Austin, and Mexico City. In selecting ground stations, compromises have to be made between the ideal and practically available ground sites, according to the simulation results obtained in Section 5.3.1. We know that we need to have at least one low latitude (≤10°) ground station to support SASSE. Thus, some of the pairs obtained from Table 21 are not useful. The ground locations that stand out and can be used for the second round simulation are Maui, Las Palmas, Trinidad, Guam, Austin, Mexico City, Kourou Island, and Johnston Island.

	L. P.	Kourou	Trinidad	Quito	Miami	Austin	M. C.	Maui	Johnston	Guam
L. P.(15)	0	38	47	63	65	83	84	**142**	**155**	200
Kourou(53)	-38	0	9	25	27	45	46	**104**	**117**	162
Trinidad(62)	-47	-9	0	16	18	36	37	**95**	**108**	153
Quito(78)	-63	-25	-16	0	2	20	21	79	92	**137**
Miami(80)	-65	-27	-18	-2	0	18	19	77	90	**135**
Austin(98)	-83	-45	-36	-20	-18	0	1	59	72	**117**
M. C.(99)	-84	-46	-37	-21	-19	-1	0	58	71	**116**
Maui(157)	**-142**	**-104**	**-95**	-79	-77	-59	-58	0	13	58
Johnston(170)	**-155**	**-117**	**-108**	-92	-90	-72	-71	-13	0	45
Guam(215)	-200	-162	-153	**-137**	**-135**	**-117**	**-116**	-58	-45	0

Table 21: 10 potential low latitude ground sites longitude differences.

With this set of ground terminal locations obtained from the ground station longitude effect analysis, the 8-step perturbation analysis is performed again to reevaluate the network performance and to obtain the optimum practical ground station locations.

5.4 Testing And Verification

LEO4CAST uses the stochastic approach to forecast network capacity and mission-to-mission conflict at a ground station for supporting multiple LEO missions. To verify the validity of LEO4CAST stochastic approach and the significance of the optimization results, the deterministic simulation tool, TERASCAN, is utilized to simulate the view periods for 2 missions at 2 random dates. EUVE and SAMPEX are the two LEO missions selected and the two randomly chosen dates are 9/21/1994 and 10/6/1994. The orbital parameters for the deterministic simulation are the 2-line mission orbital elements obtained from the electronic billboard service provided by the Naval Space Surveillance Center (NSSC) of the North American Air Defense (NORAD).

Simulations for EUVE are performed at potential ground station locations Quito, Kourou, Trinidad, Guam, Maui, Las Palmas, and JPL (DSN) for each of these two dates. A 5° minimum elevation angle is used for all simulations. The EUVE view periods for each pass at each ground station are summarized in Table 22 and Table 23. The number of passes that are longer than 8min and the total length of available contact time are listed in the tables. The ground station location that provides the longest total contact time is highlighted.

# of passes	Quito	Kourou	Trinidad	Guam	**Maui**	Las Palmas	JPL
Latitude	0	5	10	13	**21**	28	34
Pass #1	10:10	06:30	06:50	10:10	**09:10**	08:40	08:10
Pass #2	09:00	09:30	05:20	08:50	**09:50**	10:10	03:10
Pass #3	06:10	09:50	10:10	06:10	**10:10**	10:10	08:50
Pass #4	10:10	04:50	09:10	06:30	**07:40**	10:10	09:50
Pass #5	08:30	09:10	05:10	09:10	**08:10**	09:10	09:30
Pass #6	06:30	10:10	05:10	10:10	**10:10**	02:30	N/A
Pass #7	N/A	N/A	09:10	07:30	**09:40**	N/A	N/A
Pass #8	N/A	N/A	10:10	08:30	N/A	N/A	N/A
# of passes>8 min	4	4	4	5	**6**	5	4
total min of pass>8 min	37:50	38:40	38:40	46:50	**57:10**	48:20	36:20
Avg min/pass	09:28	09:40	09:40	09:22	**09:32**	09:40	09:05

Table 22: EUVE view periods at 7 ground sites for the day 09/21/1994.

# of passes	Quito	Kourou	Trinidad	Guam	**Maui**	Las Palmas	JPL
Latitude	0	5	10	13	**21**	28	34
Pass #1	09:10	07:30	09:00	09:50	**03:50**	06:40	07:10
Pass #2	10:00	10:10	10:00	09:30	**09:40**	09:50	09:20
Pass #3	05:10	08:00	07:30	04:40	**10:10**	10:10	09:30
Pass #4	09:10	06:50	07:30	10:00	**09:10**	10:10	08:50
Pass #5	09:50	10:10	10:00	09:30	**09:20**	09:50	04:40
Pass #6	05:10	08:40	08:50	06:50	**10:10**	07:20	N/A
Pass #7	N/A	N/A	N/A	05:30	**09:10**	N/A	N/A
Pass #8	N/A	N/A	N/A	07:40	N/A	N/A	N/A
# of passes>8 min	4	4	4	4	**6**	4	3
total min of pass>8 min	38:10	37:00	37:50	38:50	**57:40**	40:00	27:40
Avg min/pass	09:33	09:15	09:28	09:43	**09:37**	10:00	09:13

Table 23: EUVE view periods at 7 ground sites for the day 10/06/1994.

From the simulation results shown in Table 22 and 23, Maui stands out as the best ground station location to support EUVE on both dates. Maui provides 6 EUVE passes, each of which is longer than 8min. The total amount of available contact time at Maui is close to an hour. Las Palmas provides 5 EUVE passes and a total of 48min contact time on 9/21/1994. It provides 4 EUVE passes and a total of 40min contact time on 10/06/1994. Las Palmas is clearly the second best among all the ground stations considered. However, its average view periods per pass is close to 10min, which is longer than that of Maui on both dates. This observation gives an explanation for the discrepancy observed in Section 5.3, where the LEO4CAST simulation results show that Las Palmas is a better ground station location than Maui to support LIA missions, even though Maui has a better Q factor. The reason is that the longer average view period duration at Las Palmas results in lower probability for mission-to-mission conflict when multiple missions are supported at this ground station.

# of passes	Fairbanks	Thule
Latitude	65	76
Pass #1	0:09:20	0:02:10
Pass #2	0:10:00	0:02:30
Pass #3	0:07:00	0:07:10
Pass #4	0:02:00	0:09:10
Pass #5	0:09:00	0:09:50
Pass #6	0:09:40	0:09:50
Pass #7	0:08:10	0:09:30
Pass #8	0:05:00	0:09:30
Pass #9	0:04:10	0:09:50
Pass #10	0:07:20	0:09:50
Pass #11	N/A	0:09:00
Pas #12	N/A	0:06:40
# of passes>8 min	5	8
total min of pass>8 min	0:46:10	1:16:30
Avg min/pass	0:09:14	0:09:34

Table 24: SAMPEX view periods at Fairbanks and Thule for the day 09/21/1994.

As the latitude of ground stations increases, their performance for supporting EUVE worsens. JPL(DSN) experiences the worst performance among all the ground station locations considered, in terms of both the available number of passes and the total contact time per day. This result is consistent with the ones from the individual mission Q factor as well as the L_n analysis. It shows that the deterministic simulation results are consistent with those from the stochastic analysis. It also verifies that the probabilistic analysis approach is a valid solution to this performance optimization process as long as the analysis is intended for a long forecasting interval.

Another important observation is that Trinidad and Guam actually provide the most number of passes per day, some of which do not satisfy the 8min minimum contact time per pass requirement. However, had this requirement been changed from 8min to 6min, clearly, Guam would stand out as the optimal ground station to support EUVE. This further indicates that the required minimum contact time per pass is an important parameter that can affect the outcome of the optimal ground station analysis.

Using TERASCAN, similar simulations are performed for SAMPEX at Thule and Fairbanks for the same two dates, 09/21/94 and 10/6/94. The number of passes per day at each ground location, their associated view periods, the number of valid passes (≥ 8min), as well as the total available contact time per day are summarized in Table 24 and 25.

# of passes	Fairbanks	Thule
Latitude	65	76
Pass #1	0:08:50	0:06:50
Pass #2	0:08:10	0:09:00
Pass #3	0:10:00	0:10:00
Pass #4	0:09:00	0:10:10
Pass #5	0:06:20	0:10:00
Pass #6	0:04:50	0:10:00
Pass #7	0:07:10	0:10:20
Pass #8	0:10:00	0:10:30
Pass #9	0:10:40	0:10:00
Pass #10	N/A	0:08:10
Pass #11	N/A	0:04:30
Pas #12	N/A	N/A
# of passes>8 min	6	8
total min of pass>8 min	0:56:40	1:28:10
Avg min/pass	0:09:27	0:11:01

Table 25: SAMPEX view periods at Fairbanks and Thule for the day 10/06/1994.

It is clearly shown from the simulation results that a higher latitude location provides a lot more available passes for a HIA mission. Thule has about 30min more total available contact time per day than Fairbanks does on both dates. Thule dominates in every category and is proven to be a better ground location than Fairbanks in supporting HIA missions. The simulation results are very much consistent with the stochastic analysis results. The deterministic simulation tool verifies the validity of the LEO4CAST simulation as well as this optimization analysis procedure.

5.5 Conclusions

This section has shown some of the most important simulation results following the analysis approach described in Chapter 4. Some practical issues, such as political environment and security issues, ground station location frequency interference, command uplink, weather, geological factors of ground station locations, emergency ground support, and terrestrial communication systems for data distribution, have been left out of the analysis. This analysis has only focused on the technicality side of the LEONET ground terminal location optimization. Specifically, the analysis has only considered the network performance (lost time) due to insufficient ground station capacity.

The optimal network ground terminal locations for the 4 terminal network and 3 terminal network configurations have been obtained. For their given network load distribution schemes, each configuration results in L_n=1.51% and L_n=5.47% respectively. Las Palmas, Guam, Trinidad, Maui, and Thule are good ground locations to support these 10 LEO missions. For the 3 terminal network case, Trinidad, Maui, and Thule can be utilized as ground station locations. If 4 terminals are desired in the network, either Las Palmas or Guam can be considered.

Several conclusions can be drawn from this network performance analysis. Tradeoffs exist between the 4 and 3 terminal network configurations. Even though a 4 terminal network has a 1.51% L_n and a 3 terminal one has a 5.47% L_n, the 4 terminal network has to deal with the extra cost of operating and maintaining an additional ground terminal at different ground station. Furthermore, for these two network configurations, L_n=1.51% and L_n=5.47% may not represent their best performances. This is because the load distribution schemes employed for each configuration are not yet optimal.

As mentioned earlier, an optimal load distribution scheme will result in an equal subnet lost time percentage at each ground station. It is necessary to use a computer program, whose algorithm is governed by Equation 16, to obtain the optimal load distribution scheme for each network configuration. However, obtaining such a program is beyond the scope of this work. Furthermore, a better load distribution scheme can improve the network performance for the given 4 and 3 terminal network configurations, but it will not affect the network optimal ground locations themselves. The ground terminal locations for the 3 and 4 terminal network configurations have already converged to a set of stable solutions even though the load distribution schemes have not. For the purpose of this report, since we are only concerned with the optimal ground terminal locations, it is not necessary to obtain the absolute best load distribution schemes for the 4 and 3 terminal network configurations.

Nevertheless, it is found that a more efficient load distribution scheme can improve the network performance. Thus, a centralized network is more desirable than a decentralized first-come-first-serve system for LEONET. Due to LEONET operation characteristics, using batch processing of a centralized control system to produce load distribution scheme and to schedule downlink passes is more efficient than a decentralized control system. Hence, a centralized control system can maximize the network performance.

Trinidad is a necessary ground station to support SASSE. Maui and Las Palmas are the best locations to support other LIA missions such as EUVE and GRO. Whether a 3 terminal or a 4 terminal network configuration is desired, Thule remains the best available high latitude ground station with established NASA infrastructure. If the 4 terminal network is considered, there is a tradeoff between placing the fourth terminal at Guam and placing it at either Maui or Las Palmas. As a well established NASA base, Guam has numerous support advantages of security and communication, but it is not as efficient as Maui or Las Palmas for supporting this set of LIA missions in terms of the subnet performance due to its lower ground latitude.

These analysis results very much depend on the mission and network performance requirements. The obtained optimal ground terminal locations are specifically for the 10 LEO missions under this study. These locations would not necessarily be optimal should the mission set or mission requirements vary. Unfortunately, the requirements are often altered, especially when missions have passed their prime phases. The mission equipment condition, mission characteristics and objectives, operational budgets, and PI's willingness to negotiate and to make compromises with the network control office can change the outcome of mission requirements. However, as the number of ground terminals in the network increases, the network sensitivity to mission requirements reduces.

Close to 40% of all current and future NASA LEO missions require multiple ground stations to support their downlink requirement. It has been argued in this report that the network will be more efficient if only one terminal is located at each ground station. For each of the 40% of LEO missions which require multiple ground station support, it is neither possible nor desirable to allocate each mission its very own ground terminal (or its own network) to support its requirements. Because of these two reasons, it is more cost effective if LEO missions are cross-supported at different ground stations within the network.

For the foreseeable future, more remote-sensing LEO missions will be launched into orbits. The majority of these missions have either high or low inclination angles. Very few missions have moderate inclination angles. From the analysis results, we have learned that, to efficiently support these HIA and LIA mission requirements, the desired ground station locations should have either high or low latitudes respectively. Domestic station locations (within the continental United States) have neither very high nor very low latitudes and hence are not as attractive as many high or low latitude foreign ground locations. Furthermore, the longitude span of continental United States (except for Hawaii and Alaska) is about 40°. Hence, from the ground station longitude effect analysis, we know that confining ground terminal locations to within the continental United States probably will not result in a very efficient network. In other words, attractive low or high latitude foreign ground locations on the other side of Earth have to be considered during the design of the network.

Chapter 6 Summary

This report has introduced an analysis approach and a procedure to optimally locate ground terminals to support LEO missions with low-cost LEO-D type terminals. As the first step for this analysis, a set of 10 typical LEO missions was selected as the base mission set. They are good representatives of the 37 LEO missions, which in turn have been chosen to represent all current and future NASA near Earth missions that will be launched into space by the year 2000.

The stochastic simulation tool, LEO4CAST is utilized as the core engine of this analysis procedure. It is used to perform Q factor and mission-to-mission conflict analyses, results of which are used to produce L_s and L_n. Because there is no closed-form solution to this optimization analysis, a heuristic methodology with a perturbation analysis approach is used to obtain the optimal network configurations. Two iteration loops are constructed to deal with the interdependent relationship between the optimization of ground terminal locations and that of the network load distribution schemes.

First, a bench mark analysis is performed to obtain the minimum number of ground terminals necessary to support all 10 LEO missions at a given ground station. The geometric advantages of ground terminal locations is then utilized to improve the network performance. The latitudes of ground station locations with the least Q factor (for supporting each individual LEO mission) are obtained. LIA and HIA missions are found to be better supported at low and high latitude ground stations respectively. As a result, these 10 LEO missions are placed into three groups according to their mission inclination angles. The first order ground terminal locations for supporting each group can then be obtained.

The load distribution scheme is subsequently introduced into the optimization process to improve network performance. After many iterations and perturbations, a set of ground terminal locations for LEONET is found to best support these 10 LEO missions. Thule, Trinidad, and Maui are recommended if a 3 terminal network is desired, and they result in a 5.74% L_n. Either Las Palmas or Guam can be added to the list if a 4 terminal network is desired and L_n can be further reduced to 1.51%.

This study has demonstrated a generic heuristic analysis procedure to locate optimal ground terminal locations for LEONET to support specified LEO missions. This procedure can be applied not only to this set of LEO missions under study, but also to any given set of one or more current and future LEO missions.

There are many other topics that are both essential and interesting for the continuing research on LEONET architecture and its performance. One of the most important topics that needs to be addressed is the uplink capability of LEONET. This LEONET analysis has only dealt with mission telemetry downlink, while the mission command uplink is assumed to be supported at either WSTF utilizing TDRSS, or DSN using its 26m antenna subnet, or Wallops Island ground facility. LEONET cannot be fully and efficiently utilized as a complete and independent ground network to support LEO missions without its uplink capability. Currently, the LEONET uplink feasibility using LEO-D type terminal with a small aperture (3m~5m) antenna is under study in section 339 at JPL.

The terrestrial communication systems used for data distribution in LEONET depend on the ground station infrastructure. Ethernet, ISDN, microwave link, and fiber link are all possible candidates. Ethernet occasionally raises security issues because of its architecture and its Carrier Sense Multiple Access with Collision Detection, but at least for now, it is completely free of charge. ISDN is the emerging ground communication architecture of the future utilizing point-to-point fast circuits. It provides very high speed and bandwidth for data transmission and can be rather easily incorporated into LEONET and also into PI's local network. The selection of LEONET terrestrial communication systems depends on the availability of these communication systems at each ground location. Operational cost also has to be taken into the consideration.

The data distribution utilizes commercially available terrestrial communication systems whose reliability issues have already been considered. However, storage devices can be allocated at each ground station to temporarily store received telemetry data should there be a terrestrial communication system breakdown. The data can be distributed at a later time when the system is backed up.

The reliability of LEONET ground systems for receiving spacecraft telemetry data should be considered separately. The probability of experiencing serious breakdown in LEONET ground systems, such as antenna controllers and receivers, as well as the expected downtime due to such a breakdown are best kept under a required level. A duplicated ground terminal (at least some duplicated major components of a ground terminal) can be installed at one ground station to reduce the probability of system failure and the expected downtime. Components sharing between one or more, same or different, ground receiver systems at a ground station can also improve the network reliability while keeping the network cost within a reasonable range.

There are still many other tradeoff issues that have to be addressed before the actual LEONET design. This study has focused on a very specific aspect of LEONET, that is, how to optimally locate ground terminals to improve network performance. The analysis results have some important implications to the design of LEONET architecture. However, they are not a complete set of solutions to the entire LEONET system and performance analysis. More future in-depth research on LEONET has to be performed to deal with those numerous issues.

Chapter 7 Appendices

7.1 Simulation Tools

• The Link Budget Analysis program written in Microsoft EXCEL. It is developed at JPL. The program is used to perform link analysis on the telemetry downlink channel data margin, carrier margin, and required antenna aperture size for each LEO mission.

• LEO4CAST simulation tool developed in Section 311. LEO4CAST takes stochastic approach to tackle the long term forecasting and ground station performance analysis. It utilizes mission orbital information, downlink requirements, and ground station parameters to compute average mission-to-mission conflicts and station load conditions. These intermediate results are used to generate network performance metrics.

• GRAPHER program for PC. It is used to analyze LEO4CAST intermediate results.

• TERASCAN software provided by Sea Space Corporation in San Diego, California. It is a deterministic simulation tool that schedules downlink passes for some current in-flight LEO missions. TERASCAN is utilized as the deterministic program to perform test and verification on the LEONET stochastic analysis approach and its results.

• PC-TRACK simulation tool developed by Thomas C. Johnson and Acme Workshop. It utilizes LEO mission 2-line orbital elements to simulates satellites on a PC platform. It simulates missions trajectories and displays footprints and many other information both graphically and numerically. PC-TRACK provides an visual aid for the LEONET analysis.

7.2 LEO4CAST View Period Generation Process[51]

A reference vector of spacecraft radius, latitude and longitude for one orbit period (with a resolution of 300 time points over the orbit period), is generated by using the ordinary differential equation for true anomaly, ψ,

$$\text{(1)} \quad \overset{o}{\Psi}(t) = \frac{2\pi}{\tau(1-e^2)^{3/2}}(1 + e\cos\Psi(t))^2$$

where τ is the orbit period, e is the eccentricity. The reference value of the ascending node, Φ_o, is 0^o.

The great circle of the spacecraft ground track is given by

$$\text{(2)} \quad \sin(\delta(t)) = \sin(i)\sin(\Psi(t) + \omega)$$

$$\text{(3)} \quad \tan(\alpha(t) + \Omega_{\oplus} * t - \Phi_0) = \cos(i)\tan(\Psi(t) + \omega)$$

where i is the spacecraft orbit inclination,

$(\delta(t), \alpha(t))$ are the spacecraft latitude, longitude at time t,

$\Omega_{\oplus}$ is the ascending node correction which includes the rotation rate of the Earth,

Φ_0 is the spacecraft ascending node $(\Phi_0 \equiv \alpha(t=0) \& \delta(t=0) \equiv 0)$,

ω is the argument of perigee.

In computing view period rise and set times, each point on the spacecraft ground track has a view period circle surrounding it. This view period circle is the limit of possible spacecraft to station views, with a station horizon mask angle set to 5°. As the spacecraft moves along its orbit this circle moves with it and changes radius as the spacecraft changes its altitude (elliptical orbits). The time when this circle first touches the ground station location is the rise time, when the station exits, the set time. The view circle half angle, θ, defined for the cone from the center of the earth to the view period circle, is given by,

[51] Most of the information in this subsection in the appendices was originally reported in an inter-office memo by George Fox and Chet Borden. For more information on LEO4CAST, see LEO4CAST manual by George Fox.

(4) $$R_{\oplus} / R(t) = \cos(\theta(t)) - \sin(\theta(t)) * \tan(m)$$

where m is the horizon mask angle and m=10°,

$R_{\oplus}$ is the Earth equatorial radius at the station and $R_{\oplus}$=6378.14 km.

The spacecraft radius is given by

(5) $$R(t) = \frac{a(1-e^2)}{1 + e\cos\Psi(t)}$$

where a is the semi-major axis.

To find the view period rise and set times, adjust the reference track for the desired ascending node value by shifting spacecraft longitude values, then search the orbit vector for the start and end of feasible station views, i.e. find orbit points at times t = t_1 and t_2 such that

(6) $$\cos(\theta(t)) = \sin(\delta(t)) * \sin(\delta_0) + \cos(\delta(t)) * \cos(\delta_0) * \cos(\alpha(t) - \alpha_0)$$

where (δ_0, α_0) are the latitude and longitude of the ground station. The view period length is simply the difference between the set time and the rise time.

The average of these view periods for all ascending nodes values is used to compute the view period ratio. The average view period ratio, ρ, is

(7) $$\rho = \int_{-\pi}^{\pi} (|t_2(\Phi_0) - t_1(\Phi_0)| / \tau) d\Phi_0 / (2\pi)$$

where t_1, t_2 are the view period rise and set times for orbits with ascending node Φ_0.

When the spacecraft radius is constant, the great circle arc length, ρ_{12}, between rise and set times is given by

(8) $$\cos(\rho_{12}) = \sin(\delta_1) * \sin(\delta_2) + \cos(\delta_1) * \cos(\delta_2) * \cos(\alpha_2 - \alpha_1)$$

where (δ_1, α_1) *and* (δ_2, α_2) are spacecraft latitude and longitude at the rise and set times. For this case replace the integrand in Equation (7) with $\rho_{12}/(2\pi)$, as orbit velocity is constant.

7.3 The Long Term Forecast Of Station View Periods

Concepts from the theory of dynamic systems are used to simplify the calculation of the two dimensional integral representing the fraction of the time that a mission is visible from a particular ground station. The field flow generated from trajectories with arbitrary ascending nodes crosses the view period circle surrounding the ground station location. The integral of arc length by ascending node over the area of this view period *circle* normalized by $\tau \times (2\pi)^2$ is the view period ratio, ρ. Here we have assumed: 1) That orbit period of the spacecraft is such that there are no quasi-repeating ground tracks. This condition assures the ergodic property, where time integrals ≡ space integrals, so that trajectory field flows preserve area. 2) The Earth's rotation rate and gravitational corrections due to oblateness are small and can be neglected. 3) The view period *circle* is a circle, i.e. orbit eccentricity is 0, giving a constant spacecraft orbit radius and hence constant θ, the view period cone half angle.

Using the notation from appendices 9.1, Equation (3), the view period ratio is written as

$$\rho = \int_{\underline{\delta}}^{\overline{\delta}} \frac{2\cos\delta \ \arccos\left(\dfrac{\cos\theta - \sin\delta\sin\delta_0}{\cos\delta\cos\delta_0}\right)}{\sqrt{\sin^2 i - \sin^2\delta}} \frac{d\delta}{\tau(2\pi)^2}$$

where $\underline{\delta}$ is the lower bound on latitude given by the greater of $-|i|$ and $\delta_0-\theta$, $\overline{\delta}$ is the upper bound on latitude given by the lesser of $|i|$ and $\delta_0+\theta$. Since area is preserved for the ergodic system, the complicated orbit paths across the view period region are replaced by simple arcs from the view period circle to its center, each arc weighted by $\cos\delta/(\sin^2 i-\sin^2\delta)^{1/2}$.

7.4 Information Of Un-Selected 27 LEO Missions

Information for the 10 selected LEO missions used for this analysis are listed in Table 8 to Table 10 in Chapter 3. The other 27 un-selected LEO mission parameters are shown in Table 26 to Table 28.

Missions	Launch Date	End Prime Mission	End Ext Mission	Perigee (km)	Apogee (km)	Inclination (deg)
ACME 1	08-01-1995	08-30-1995	TBD	250.00	5800.00	TBD
ACME II	08-01-1997	01-30-1998	TBD	200.00	200.00	TBD
ASTRO-D	02-20-1993	03-10-1996	01-07-2000	536.00	642.00	31.10
AXAF S	12-01-1999	11-30-2002	TBD	900.00	900.00	99.00
COBE	11-??-1989	11-??-1992	TBD	900.00	900.00	TBD
EHIC	TBD	TBD	TBD	833.00	833.00	99.00
HESP	06-01-1999	05-31-2002	TBD	600.00	600.00	97.79
JUNO	06-01-1997	11-30-1998	11-30-2000	600.00	600.00	0.20
NIMUBUS-7	10-24-1978	01-04-1990	12-30-1999	944.00	968.00	99.00
NOAA-K	03-01-1995	04-30-1995	02-28-1997	833.00	833.00	99.00
NOAA-L	07-01-1996	08-30-1996	07-01-1998	870.00	870.00	99.00
NOAA-M	01-01-1997	03-02-1997	01-01-1999	833.00	833.00	99.00
NOAA-N	03-01-1999	04-30-1999	02-28-2001	870.00	870.00	99.00
POEMS	06-01-1997	TBD	TBD	600.00	600.00	97.79
RADARTSAT	02-01-1995	02-01-2000	TBD	792.00	792.00	98.50
ROSAT	06-01-1990	12-31-1995	TBD	580.00	580.00	53.00
STEP	09-01-1999	05-13-2000	TBD	550.00	550.00	97.84
TIMED L	12-01-1999	11-30-2001	TBD	400.00	400.00	49.00
TOPEX/POS	08-10-1992	08-10-1995	08-10-1997	1336.00	1336.00	66.04
TOPEX II	06-01-1997	05-31-2000	06-01-2002	1300.00	1300.00	66.00
TOPEX IIb	TBD	TBD	TBD	800.00	800.00	108.00
TOPEX IIc	TBD	TBD	TBD	700.00	700.00	98.20
TOPSAT	03-01-1998	08-30-1998	05-31-1999	564.00	564.00	97.50
TRMM	08-01-1997	12-31-2000	12-31-2001	350.00	350.00	35.00
WFXT	06-01-1998	06-01-2002	TBD	550.00	550.00	3.00
WIRE	12-01-1997	03-31-1998	TBD	400.00	400.00	97.03
YOHKOH	08-26-1991	08-25-1994	08-26-1999	515.00	770.00	31.10

Table 26: The un-selected 27 LEO missions parameters, part (a).

Missions	Downlink Freq	Downlink Rate	Req. Contact	RF Power	Slant Path	Free Space Loss
	(MHZ)	(KBPS)	(min/day)	(W)	(km)	(dB)
ACME 1	S Band	2	240	1.00	9833.31	TBD
ACME II	X Band	1000	480	TBD	1147.13	TBD
ASTRO-D	2256.22	262.14	40	0.50	2429.19	167.22
AXAF S	2287.50	512	TBD	TBD	2993.71	TBD
COBE	2287.50	655.36	TBD	5.00	2993.71	169.15
EHIC	TBD	TBD	TBD	TBD	2854.23	TBD
HESP	S Band	6600	60	TBD	2329.03	TBD
JUNO	TBD	TBD	TBD	TBD	2329.03	TBD
NIMUBUS-7	2211.00	800.00	90	TBD	3131.13	TBD
NOAA-K	2247.50	16.6	96	TBD	2854.23	TBD
NOAA-L	2247.50	16.6	96	TBD	2931.79	TBD
NOAA-M	2247.50	16.6	96	TBD	2854.23	TBD
NOAA-N	2247.50	16.6	96	TBD	2931.79	TBD
POEMS	TBD	TBD	TBD	TBD	2329.03	TBD
RADARTSAT	2230.00	128	30	TBD	2766.65	TBD
ROSAT	2276.50	1000	20	TBD	2280.31	TBD
STEP	2290.00	326.00	15	1.00	2205.90	166.51
TIMED L	2287.50	3000	15	5.00	1804.52	TBD
TOPEX/POS	2287.50	1024.00	60	5.00	3818.62	171.27
TOPEX II	TBD	TBD	TBD	TBD	3754.82	TBD
TOPEX IIb	TBD	TBD	TBD	TBD	2783.88	TBD
TOPEX IIc	TBD	TBD	TBD	TBD	2563.15	TBD
TOPSAT	S Band	500	333	20.00	2240.83	TBD
TRMM	S Band	2000	224	10.00	1656.85	TBD
WFXT	TBD	TBD	TBD	TBD	2205.90	TBD
WIRE	S Band	1250	20	5.00	1804.52	TBD
YOHKOH	2256.22	262.14	55	0.50	2718.90	168.20

Table 27: The un-selected 27 LEO missions parameters, part (b).

Missions	Ant Gn	Ckt Loss	Xmt EIRP	Un/coded	Reqd Eb/No	Carrier Margin	Data Margin
	(dB)	(dB)	(dB)		(dB)	(dB)	(dB)
ASTRO-D	-2.00	-6.20	-11.21	Uncoded	9.68	13.70	-6.59
COBE	-9.00	-2.50	-4.50	R=1/2,7,Conv	4.46	22.06	-1.34
STEP	-1.30	-2.10	-3.40	R=1/2,7,R/S	2.40	21.49	7.52
TOPEX/POS	2.00	-7.60	1.40	Uncoded	9.68	25.85	-4.72
YOHKOH	-13.00	-3.20	-20.20	Uncoded	9.68	3.73	-16.56

Table 28: The un-selected 27 LEO missions parameters, part (c).

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Acronyms

BER	Bit Error rate
CCSDS	Consultative Committee for Space Data Systems
DCT	Design Control Table
DTG	Direct To Ground
DSN	Deep Space Network
EUVE	Extreme Ultraviolet Explorer
FAST	Fast Auroral Snapshot Explorer
GPS	Global Positioning System
GRO	Gamma Ray Observer
GSFC	Goddard Space Flight Center
HEO	Highly Elliptical Orbit
HIA	High Inclination Angle
HGA	High Gain Antenna
IRTS	Infrared Telescope in Space
ISAS	Japanese Space Agency
ISDN	Integrated Services Digital Network
JPL	Jet Propulsion Laboratory
LIA	Low Inclination Angle
LEO	Low-Earth Orbiter
LEONET	Low-Earth Orbiter Network
LEO-D	Low-Earth Orbiter terminal Demonstration
LDC	Load Duration Curve
LZ	Level-Zero
MIA	Moderate Inclination Angle
NASA	National Aeronautics and Space Administration
NASCOM	NASA Ground Communication System
NORAD	North American Air Defense

NSSC	Naval Space Surveillance Center
PI	Principal Investigator
POPS	Planetary Orbiter Planning Software
PPC	Pre- and Post- Calibration
SAC-B	Satellite de Aplicaciones Cientificas-B
SAMPEX	Solar, Anomalous, and Magnetospheric Particle Explorer
SASSE	Small Astrophysical & Solar Spectrometer Explorer
SFU	Space Flyer Unit
SMEX	Small Explorer
SWAS	Submillimeter Wave Astronomy Satellite
TDRSS	Tracking and Data Relay Satellite Systems
TOMS-EP	Total Ozone Mapping Spectrometer - Earth Probe
TOPEX	Ocean Topography Experiment
WSTF	White Sands Test Facility
XTE	X-ray Timing Explorer