Evaluating the Dependability of a LEO Satellite Network for Scientific Applications

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Abstract

Dependability is an important issue in LEO satellite networks. In this paper, we study the dependability of a proposed LEO satellite network for scientific data collection based on the Illinois Observing Nanosatellite (ION). In particular, we first use analytical techniques to determine the amount of radiation shielding and number of redundant components, such as batteries and regulators, needed to achieve particular reliability goals for an individual satellite. We then incorporate the satellite model into a larger satellite network model to analyze network performance and dependability using simulation. Both models are represented as stochastic activity networks (SANs) in Möbius, making it possible to combine them and choose the best solution technique (analytical vs. simulation). Our results show how accumulated radiation dosage affects the functioning of the proposed network, and how redundancy and shielding can be profitably used to increase dependability.

1. Introduction

In this paper, we study the dependability of a proposed satellite network that collects data for scientific applications. Possible scientific applications include natural disaster monitoring, earthquake monitoring [1], mapping of the Earth's magnetic field, and measurement of radiation flux for space weather. Our first goal is to study dependability of the Illinois Observing Nanosatellite (ION) [2] and incorporate insights from this study into its successors. In October of 2005 ION is scheduled to be the University of Illinois's first student-developed satellite to launch into space. The scientific experiment that ION runs involves measurement of light emissions from oxygen chemistry in the atmosphere. ION has a six-month target lifetime due to a short mission requirement and the use of Commercial Off The Shelf (COTS) components. We study in detail how the satellite's components affect its overall reliability and availability, with the aim of supporting longer-duration missions in the future. In particular, we study how radiation shielding and component redundancy affect the satellite's reliability in the presence of accumulative radiation effects known as Total Ionizing Dose (TID).

Once we study in detail the dependability of a single satellite, our next goal is to study how sharing resources through a network could improve communication with the ground. If satellites do not share communication resources through a network, communication is limited; each satellite passes over the ground station roughly twice per day for fifteen minutes each time, providing very restrictive maximum communication time for each satellite. More importantly, such infrequent contact makes command and control more difficult, especially during the first few critical weeks of operation. In order to study the potential benefits of the network, we incorporate the dependability model for the individual satellite into a satellite network model. The dependability of individual satellites affects the network, since the satellites lose data when they experience temporary failures, and they cannot communicate when they are temporarily or permanently down. Using our network model, we study a simple routing technique with moving Low Earth Orbit (LEO) satellites, limited storage capability, limited data collection and transfer rates, and data losses. We make various measurements, such as data collected, data lost, network throughput, and average network latency.

To develop our model, we use the modeling tool Möbius [3], which allows us to build realistic system models easily. Möbius provides this capability through the use of high-level formalisms, such as stochastic activity networks (SANs) [4]. We first model ION's dependability and then easily incorporate that model into the larger network model.

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Möbius allows us to compare different architectures easily by varying parameters between simulations. These studies allow us to develop a deeper understanding of the system's critical points and can direct our design efforts more appropriately. Such a capability is particularly important for satellites since they cannot be repaired after deployment. Satellite network designers can save tens of millions of dollars in flight hardware deployment by more accurately modeling the number of satellites they need.

In particular, we explore how component redundancy and radiation shielding can be used to increase dependability profitably in the presence of TID effects for ION's successors. We use ION's mission dependability requirements to define architecture decisions. We also explore how dependability of individual satellites affects the proposed satellite network dependability and performance. We learn about the network's design limitations in the presence of satellite failures before investing effort into more detailed functional simulators or an actual implementation.

2. Problem Description

2.1. Individual Satellites and Ground Station

ION has several mission objectives, including testing of new thrusters, testing of a new processor for small satellites, testing of a CMOS camera, demonstration of attitude control on a CubeSat, and atmospheric measurements. As explained in the introduction, we use ION's atmospheric measurement experiment to define the requirements for our system. Next, we explain in detail the satellite and the ground station model specifications, and discuss the effect of radiation on dependability.

Ground Station The ground station can experience temporary failures. More specifically, the main effect that we consider is a repairable preamp failure. We assume that lightning storms cause the preamp to fail once every two months on average, and that the expected time it takes to detect and correct the failure is two days.

Satellite Subsystems The satellite consists of seven critical subsystems, as follows: the 5V regulator, the 9V regulator, the battery, the solar panel, the communication hardware, the processor, and the telemetry. All of them must operate correctly for the satellite to operate correctly, and the atmospheric experiment hardware also needs to function for the scientific experiment to succeed. A permanent failure occurs if any of the satellite's critical subsystems fail. Also, there may be temporary failure of subsystems. The processor may hang due to single event upsets (SEUs) caused by radiation-induced bit flips. Also, the 5V regulator has a fault protection feature that requires a watchdog timer-controlled power cycle for recovery. As will be explained later, we explore the effect of redundancy of some components, such as the 5V regulator, the 9V regulator, and the batteries.

Total Ionizing Dose (TID) Satellite dependability is directly affected by radiation. Steady exposure to radiation effectively accelerates the aging process of the satellite's electronic components, substantially shortening their life [5]. A recent NASA report [6] shows that Total Ionizing Dose effects on CMOS components could have a large impact on ION's dependability. We determine radiation for our orbit at various shielding levels using an on-line tool called SPENVIS [7]. Based on general guidelines given in [6], we expect a dose rate of a few krads/yr with 2.5 mm of shielding at ION's high-inclination 650 km Low Earth Orbit. The SPENVIS model predicts 2 krads for a one-year mission. ION has approximately 1 mm of shielding, which we select as the model's baseline shielding level (radiation scale factor $r = 1$). Table 1 shows all radiation scale factors we use in our model with their corresponding exposure rates.

To study how different architectures tolerate radiation, we need to understand how different components respond to radiation. Based on radiation tolerance information in [8] and [9], we estimate the failure rate due to TID at 0.007 failures per year for processor and general CMOS components and at 0.0001 failures per year for the discrete components. We perform sensitivity analysis on the satellite dependability by scaling these failure rates as shielding levels change using the radiation scale factor r as shown in Table 1.

Table 1. Radiation shielding

Shielding	Exposure rate	Radiation scale factor r
3 mm	1.5 krads/yr	0.2
2 mm	2.8 krads/yr	0.4
1 mm	7 krads/yr	1.0
0.6 mm	13.5 krads/yr	2.0
0.3 mm	35 krads/yr	5.0

Satellite Studies Given the satellite model parameterized for architectural redundancy and radiation shielding levels, we calculate various dependability measures, such as reliability at certain points in time and availability over a time interval. We perform the calculations for the satellite, the ground station, and the combined satellite/ground station system. The reliability $R(0, t)$ is the probability of no permanent critical system failures during [0, t]. Note that the reliability of the combined system equals the reliability of the satellite, because we assume that ground station failures can be repaired. The interval availability $A(0, t)$ of a system during an interval of time $[0, t]$ is the fraction of the time that the system delivers proper service during the interval $[0, t]$.

2.2. Satellite Network

Each satellite runs the same atmospheric measurement experiment and aims to transfer the collected data to the ground station using the network. The network consists of LEO satellites, so its topology changes dynamically over time as the satellites propagate through their orbits. The satellites can typically communicate with the ground station zero to two times per day for a time interval of about fifteen minutes each, and they can communicate with each other over InterSatellite Links (ISLs) zero to two times per orbit.

<u>Satellite orbits</u> We use a network of four satellites with orbits that provide an interesting case. Specifically, Satellites 1–3 operate at LEO orbits with a 90 min period corresponding to a 300 km altitude, and Satellite 4 operates at a higher orbit with a 720 min period. We also consider one ground station located in the upper hemisphere at a 45^o inclination. As shown in Figure 1, Satellites 1 and 2 follow orthogonal polar orbits (90^o inclination angle), Satellite 3 follows a 45^o inclination angle orbit, and Satellite 4 follows a 0^o inclination angle orbit. We view the dynamic LEO satellite network as a number of different static networks over discrete time steps [10]. More specifically, to simulate the periodic nature of satellite communication, we divide the orbit period of each satellite into 16 equal-length intervals, each of which corresponds to a time step. Any two satellites may communicate when they occupy the same place, and any satellite may communicate with the ground station when it is over it. As a result, the communication range equals the circumference of the orbit divided by 16 steps ($\frac{2\pi(6378 \text{ km}+300 \text{ km})}{16} = 2622$ km).

Unlike terrestrial communications systems, the topology of a LEO satellite network changes over time, since satellites can only communicate when they are in communication range. With our selection of orbits, Satellites 1 and 2 can talk to the ground twice per day, Satellite 3 can talk to the ground once per day, and Satellite 4 never passes over the ground station. In Table 2, we show the percentage of time that the satellites and the ground station communicate with each other due to their initial locations and orbits. Note that Satellites 1 and 3 do not communicate with each other and Satellite 4 does not communicate directly with the ground station.

Table 2. Communications time (%)

	Sat 2	Sat 3	Sat 4	GS
Sat 1	12.50	0	0.78	0.78
Sat 2		12.50	0.78	0.78
Sat 3			0.78	0.39
Sat 4				0

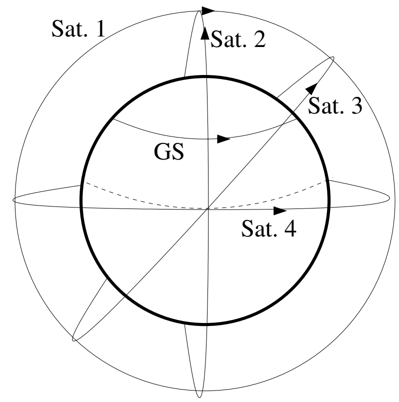

Figure 1. Earth and satellite orbits

<u>Communication</u> Each functioning satellite collects scientific data at a rate of 2000 MB/yr as long as its memory has space for the data. When a temporary or permanent failure occurs at the satellite, it loses all stored data. If the failure is temporary, then the satellite begins to collect data again when it becomes operational again. In our model, we do not include the uplink communication from the ground station to the satellites, because the uplink transmissions involve significantly less traffic compared to the downlink transmissions.

With a dynamic network arrangement, it is challenging to design a message-routing algorithm that efficiently transfers data to the ground station. We employ a simple routing algorithm as follows. When two satellites communicate, they first exchange information about how much time it will take each one of them to reach the ground station. Then the satellite that is further away from the ground station transfers data to the closer one. Independent of its location, each satellite also has the option to transfer data to the ground station through an existing commercial satellite network such as OrbComm, Iridium, or GlobalStar.

We use a communication rate for ISLs equal to 115 kbps with 50% overhead, which corresponds to an ISL rate of $\frac{115 \times 50\% \times 3600 \times 24 \times 365}{8000} = 226665$ MB/yr. We use twice that rate (453330 MB/yr) for satellite to ground station communications. The ground station has more sophisticated hardware and higher power availability, so it can communicate with the satellites at 1.5 times the maximum distance at which satellites can communicate with each other. We compensate for the longer contact period with the ground station by proportionally increasing the communication rate. We also assume that Satellite 4, which is at a higher orbit, uses a directional antenna to adequately increase its communication range directly downwards. The data transfer per year supplied by satellite constellations such as OrbComm (or Iridium) varies greatly with the cost. In this work, we use transfer rates from 0 to 1000 MB/yr.

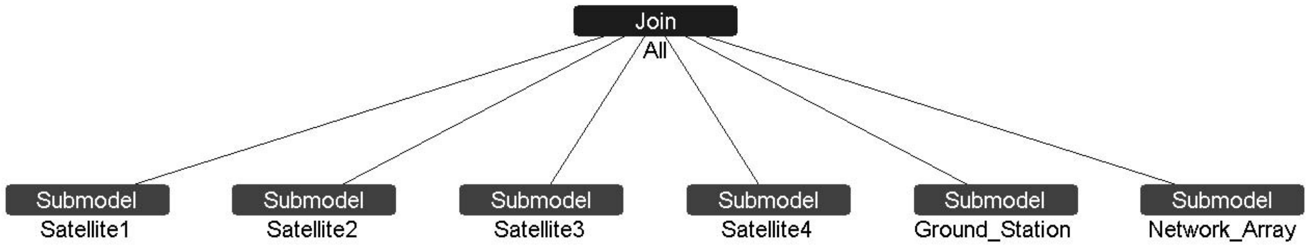

Figure 2. ION satellite network composed model

Network Studies After incorporating the individual satellite model into the network model, we measure the reliability and availability of the combined system. Additionally, we evaluate the network's performance by measuring the data collected by the network, the percentage of collected data reaching the ground station, the data lost due to permanent or temporary failures, and the average network delay. We also measure the percentage of time that satellites' memory is full and the average amount of data that resides in the satellites' memory. Limited storage capability and individual satellite dependability directly affect the network's performance.

3. Model Description

The three separate SAN models that make up our overall model are the Satellite Model, the Ground Station Model, and the Network Array Model. Due to space limitations we only include portions of the model in this paper. The full model in electronic format is available upon request. The Composed Model in Möbius (Figure 2) ties the Network Array Model to the other models by sharing permanent and temporary failure *places*. In a SAN model [4], each *place* represents the "state" of a portion of a system and contains *tokens*. Its *activities* represent actions in the modeled system that take some, possibly randomly distributed, amount of time to complete. Its *input gates* and *output gates* permit flexibility in defining activity enabling and completion rules. Each of the leaf nodes in Figure 2 is a SAN, and the Join node specifies how the individual SAN models interact with each other by sharing places. In total, the model contains 76 places, 7 extended places, and 85 activities in order to accurately represent the behavior of the system as described in Section 2.

In order to obtain various system measures, Möbius provides performance variables through reward models [11]. Möbius can calculate values for these variables using analytical state-based solution techniques and can use discrete-event simulation techniques for more complex models. We use analytical techniques for individual satellites and simulation techniques on the more complex satellite network.

3.1. Individual Satellites and Ground Station

Ground Station As discussed earlier, we model preamp failures and repairs at the ground station (Figure 3). If the *Preamp_Working* place has a token, it means that the preamp and hence the ground station are operational. The *Preamp_Failure* activity fires with a specified rate and exponential probability distribution, causing the *Preamp_Working* token to transfer to the *Preamp_Failed* place. The *Preamp_Repair* activity similarly causes the token to move back into the *Preamp_Working* place.

Satellite Subsystems As shown in Figure 3, each critical satellite subsystem is modeled as a SAN and contains tokens representing the number of redundant components of that subsystem that are currently operating. For permanent failures, the output gate for each subsystem places a token in a *Satellite_Failed* place when the subsystem is no longer operational (i.e., it has less than the required number of components working). For example, if the satellite has dual redundant batteries, then the battery subsystem initially has two tokens in its place. After the first battery failure, one token is removed. After the second failure, the second token is removed, and a token is added to the *Satellite_Failed* place.

Activities are also triggered by temporary failures of the processor and the 5V regulator, but a *System_Hang* place receives a token until another *Power_Cycle* activity removes it. For example, if the processor is operational, the *Proc_Work* place has one token. If a temporary failure such as a reset due to a single event upset occurs, then the token moves to the *Proc_Frozen* place. The satellite remains in the hanged state until the *Power_Cycle* activity fires, moving the token from the *Proc_Frozen* place back to the *Proc_Work* place.

Total Ionizing Dose As explained earlier, we divide our components into three radiation tolerance categories. Table 3 shows the number of components of each type contained in each satellite subsystem (and its corresponding model). We multiply all failure rates due to radiation by a varying scale factor, r, which essentially models different radiation

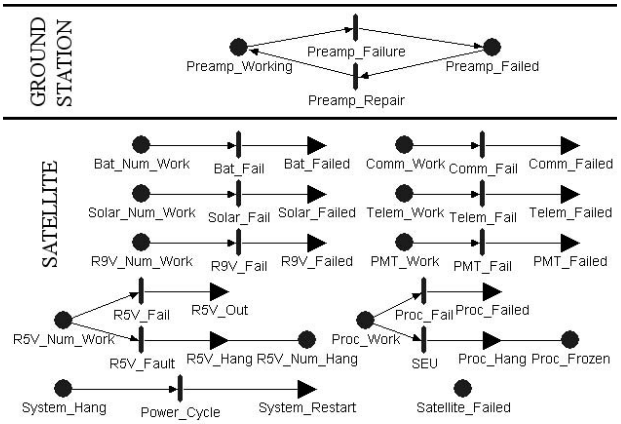

Figure 3. Ground_Station and Sat 1 model

shielding levels. We use the different values of r to assess the value of adding redundancy to the regulators and batteries under different radiation shielding levels.

Table 3. Number of subsystem components

Satellite Comp.	# CMOS	# Discrete	# Proc.
Regulator 5V	1	6	0
Regulator 9V	1	6	0
Communication	8	250	1
Processor	30	274	1
Telemetry	9	50	0
Exp. Components	29	58	0

Satellite Studies As explained earlier, our objective for the single satellite studies is to explore architectural trade-offs that affect satellite dependability. Starting with the individual satellite SAN models, we automatically generate continuous time Markov chains (CTMCs) in Möbius. Then we solve the generated CTMCs using the *transient* solver. The transient solver efficiently calculates the mean of each performance variable at particular time points using the uniformization method.

To study the effect of radiation and component redundancy, we use several global variables to parameterize model characteristics. Table 4 shows the baseline values we select for the global variables. For the first study, we vary the radiation scale factor from 0.2 to 5 in order to model different shielding thicknesses. Next, we study component redundancy by varying the number of batteries from 1 to 3 and the number of 5V and 9V regulators jointly from 1 to 3.

Table 4. Baseline values

	Value
# Batteries	2
# Regulators	1
r	1

3.2. Network Model Description

Due to space limitations we show part of the Network_Array SAN model (Figure 4) without repeated satellites. For the given scientific application, the packet sizes to be transferred are small and of fixed length; hence, the communication activities are deterministic. In fact, all activities in the network model are deterministic, as opposed to the satellite model in which exponential activities are used to model random failures.

First we make the connection with the individual satellite models by sharing the network permanent and temporary failure places with the corresponding individual satellite model's places. The ground station temporary failure place is similarly shared with the ground station model's corresponding place. Next, we explain the satellite network model in more detail.

Satellite orbits The orbit propagator offers the flexibility to support various orbits. We use Möbius's extended places with arrays [12] to track multiple satellite locations. This technique makes it easier to scale the model to more satellites, since we can access the places using code loops in the input and output gates. Two extended places (*Sat_Loc_phi* and *Sat_Loc_theta*) in the SAN model track the satellite locations with a resolution of 16 steps using a standard spherical coordinate system with variables ϕ and θ (radius is constant). Two regular places (*GS_Loc_phi* and *GS_Loc_theta*) similarly track the location of the ground station. The extended place *Sat_Loc2GS* tracks the location of each satellite relative to the ground station. A *Sat_Counter* activity steps the satellites and ground station through their predetermined locations with the appropriate period (90 min for Satellites 1–3, 720 min for Satellite 4, and 24 hrs for the ground station).

Communication We use the extended place *Sat_Queue* to track each satellite's queue size (the number of tokens represents the amount of data in the queue) and the regular place *TotalResetDataLoss* to track the total data loss due to resets. As each satellite collects data, we add tokens to that satellite's *Sat_Queue* place using the *Sat1_DataCollection* activity. We use an input gate to ensure that data is collected only while the satellite is operational and has room in its queue. In order to implement the routing algorithm discussed in Section 2.2, we use the extended place *Sat_Loc2GS* to track

Table 5. Output gate for SAN Network_Array

Output Gate	*Out_Transfer_Sat_Sat*

Function	$int\ i, j;$
	$for\ (i = 1; i <= 3; i++)\{$
	$for\ (j = i + 1; j <= 4; j++)\{$
	//Check if both satellites are not over ground station
	//Check if satellites are in same location
	//Check if both satellites have not failed
	{
	//Check if j is closer to ground station, i has data, and j not full
	$if((Sat\_Loc2GS \rightarrow Index(i) \rightarrow Mark() > Sat\_Loc2GS \rightarrow Index(j) \rightarrow Mark())\&\&$
	$(Sat\_Queue \rightarrow Index(i) \rightarrow Mark() > 0)\&\&$
	$(Sat\_Queue \rightarrow Index(j) \rightarrow Mark() < QUEUE\_SIZE))\{$
	$Sat\_Queue \rightarrow Index(j) \rightarrow Mark()++;$
	$Sat\_Queue \rightarrow Index(i) \rightarrow Mark()--;$
	...

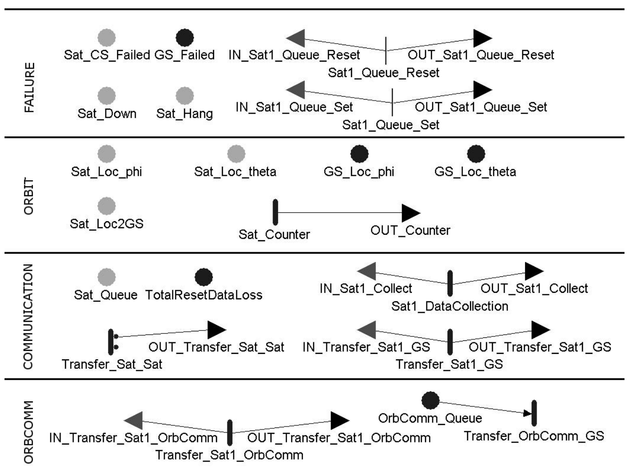

Figure 4. Part of Network_Array model

the number of steps until each satellite is over the ground station. While two satellites occupy the same location, the satellite with the lower counter value receives data from the other satellite until its queue fills or no data is left to transfer. Since we need to check whether communication is possible for each pair of satellites, scalability of the model becomes a concern. To improve scalability, the output gate *OUT_Transfer_Sat_Sat* contains code loops that access the extended places that check each pair of satellites. Table 5 shows part of that output gate function. The outer loops cycle through each combination of satellites, and the inner code determines what action should take place. The inner code first determines if intersatellite communication can occur (i.e., if the satellites occupy the same location, the satellites are not over the ground station, and both satellites are currently operating). If intersatellite communication can occur, then we check if the satellite closer to the ground station has space available in its queue. If the further satellite also has data available in its queue, then we move data from the further satellite's queue to the nearer satellite's queue by moving tokens between their *Sat_Queue* places. For satellite to ground station communication, we model each satellite-to-ground link separately. At every time step, we transfer data using the *Transfer_Sat1_GS* activity (if the satellite is over the ground station) by removing tokens from the satellite's *Sat_Queue* place.

Transfers out of the satellite queues to the OrbComm network can occur at all time steps when the activity *Transfer_Sat1_OrbComm* fires. The data is temporarily buffered in the queue *OrbComm_Queue* before moving to the ground station.

<u>Network Studies</u> We cannot use analytical solution techniques to solve the complete network model because of the size of its state space. Instead, we use the Möbius discrete event simulator. We create some performance variables to verify the model and other performance variables for study analysis. First, we test the orbit propagator by verifying the percentage of time each combination of satellite and ground station is in communication range. Then, we estimate the reliability and availability of satellites to ensure that they correspond to the earlier analytical solution for individual satellites. We also check the total number of satellite resets to ensure that they behave as designed. Finally, we ensure that data reaching the ground station, data lost, and final queue sizes together add up to the total data collected.

The performance variables created for the purpose of analysis include queue measurements such as satellite mean queue sizes and OrbComm queue size, as well as the percentage of time that satellite queues remain full. We use a place to measure the data lost and use impulse rewards to measure data collected and data received by the ground station. We estimate the average time packets spend in the network using Little's Law (the sum of data in the satellite and OrbComm queues divided by the data collection rate).

Table 6. Additional baseline values (network)

	Value
Data collection rate	2000 MB/yr
Transfer rate from sat. to GS	453330 MB/yr
Transfer rate of ISL	226665 MB/yr
Transfer rate from sat. to OrbComm	0 MB/yr
Satellite queue size	100 MB
Experiment run time	6 months
Period of Satellites 1, 2, 3	1.5 hours
Period of Satellite 4	12 hours

Finally, we measure reliability and availability of individual satellites and the ground station in addition to overall system reliability and availability.

In order to provide a basis for comparison across studies, we select the baseline configuration shown in Table 6. We explore various configurations by varying the following parameters: experiment run time, ISL on/off, satellite queue capacity, data collection rate, and OrbComm rate.

4. Results

4.1. Individual Satellites

We first present results of architectural studies on individual satellite and ground station dependability produced using analytical techniques. The models we solve have up to 17000 states and typically take less than 6 seconds to solve. As expected, the solution for the individual satellite model has an absorbing state that corresponds to a satellite failure.

Varying radiation shielding For the first study, we adjust the radiation-induced failure rates using r, and we compute the satellite reliability $[0, t]$ for $r = 0.2, 0.4, 1, 2,$ and 5. Figure 5 shows satellite critical system reliability over time for different radiation levels. As radiation shielding decreases from the baseline value ($r = 1$) (1 mm of shielding), the reliability falls rapidly to unacceptable values. Therefore, TID has a significant effect on system reliability for our mission time, and we should maintain shielding at a minimum of 1 mm.

Varying battery redundancy For the second study, we return to the baseline radiation level and change battery redundancy from the baseline value of 2. Figure 6 shows that adding a third battery does not improve reliability substantially, since the rest of the components typically fail before the batteries. However, reducing the number of batteries to 1 significantly reduces reliability. If radiation shielding is low, adding a second battery makes less difference, because radiation causes other critical system failures first. We can make decisions on battery redundancy without consideration of TID effects, since in this case battery failure is unrelated to radiation. Dual battery redundancy appears worthwhile in this case due to a high probability that one battery will fail during the interval of interest.

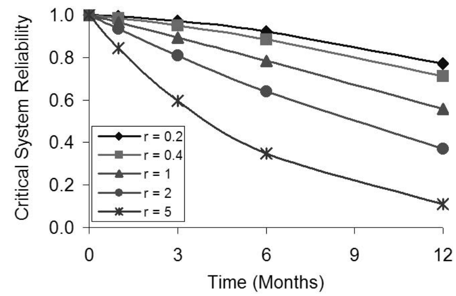

Figure 5. Reliability for varying radiation

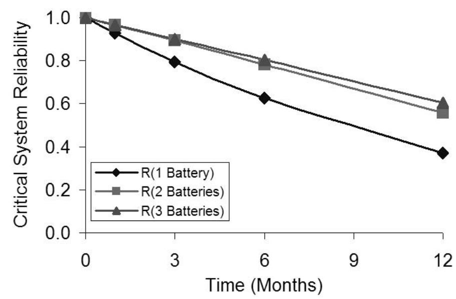

Figure 6. Reliability for varying batteries

Varying regulator redundancy For the third study, we change the regulator redundancy. In Figure 7, all curves are identical at the level of precision that is visually distinguishable on the graph. Regulator redundancy does not improve TID immunity, since the processor and communication system have many more components and fail due to TID earlier.

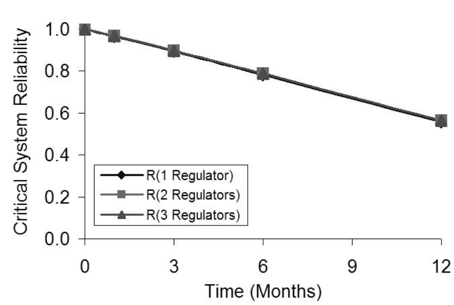

Figure 7. Reliability for varying regulators

Table 7. Baseline results

	Value
Single satellite reliability	0.800
Overall system reliability (Any)	0.985
Overall system reliability (All)	0.361
Single satellite availability	0.898
Ground station availability	0.968
Overall system availability (Any)	0.996
Overall system availability (All)	0.633
Number of resets	4.426
Data collected	3380 MB
Data received	3114 MB
Data lost	139 MB
Data left in the queues	126 MB

4.2. Satellite Network

We now present dependability and performance measures of the satellite network that we obtain using the discrete event simulator in Möbius. The running time of a single simulation ranges between 150 and 3250 seconds. The relative confidence interval of our estimates is 10% for a confidence level of 0.95. Table 7 shows the values of several dependability and performance measures for the baseline configuration. We consider the overall system to provide proper service if the ground station and any of Satellites 1–3 are operating (Satellite 4 does not directly communicate with the ground station). The overall system reliability (Any) exceeds single satellite reliability and the overall system availability (Any) is very high. It is also of interest to measure the dependability of the system when proper service requires all satellites and the ground station to operate. The overall system availability (All) in this case gives us insight into how much difficulty a packet traveling through the network will experience. The simulation measurements of single satellite reliability and availability and ground station availability agree with the analytical results from the individual satellite model. Next, we vary different parameters and make dependability and performance estimates.

<u>*Varying experiment run time*</u> As expected, the reliability of each satellite decreases over time (Figure 8). The availability of each satellite also decreases over time, because it can fail permanently. The ground station availability stays constant, because it does not fail permanently. Figure 9 shows the percentage of time satellite queues are full as a function of time. Due to the selection of orbits, Satellite 2's queue stays full more than the other satellites, since it frequently functions as an intermediate step for data transfers from Satellite 3 to the ground station. Satellite 3 transmits data to Satellite 2 75% of the time. Satellite 4 never receives

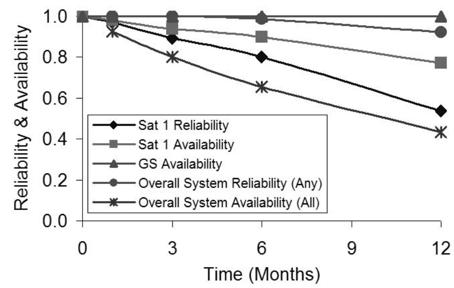

Figure 8. Dependability over time

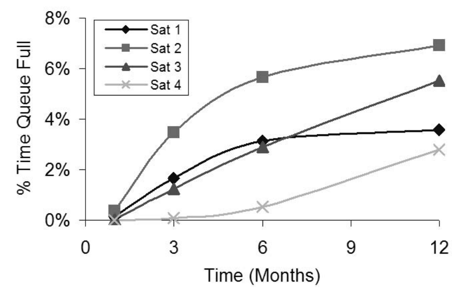

Figure 9. Filled queues over time

data from other satellites, because it has no direct communication capability to the ground station. As a result, it tends to be full the least. Note that all queues are full a small percentage of time, and this percentage grows as satellites fail, since packets must be buffered longer. Packets must be buffered longer as satellites fail because the network no longer accelerates their delivery to the ground.

<u>*ISL links versus no ISL links*</u> Next, we compare network performance with ISL links enabled against performance in the absence of intersatellite communication (Table 8). To make the comparison fair, we do not include Satellite 4, since it cannot communicate directly with the ground station. With a data collection rate of 100, the network is lightly loaded, and the average time packets spend in the network decreases by about half. When the network is loaded like in the baseline configuration (data collection rate of 2000), the performance improvement is much more dramatic. Satellite 3's queue is much larger without the net-

Table 8. ISL on/off (Satellites 1 to 3 only)

ISL On / Off	Off	On	Off	On
Data col. rate (MB/yr)	100	100	2000	2000
Sat 1 mean queue (MB)	0.08	0.06	2.20	2.66
Sat 2 mean queue (MB)	0.08	0.07	2.20	4.28
Sat 3 mean queue (MB)	0.14	0.03	61.75	5.29
Average time (days)	0.40	0.22	4.75	0.84

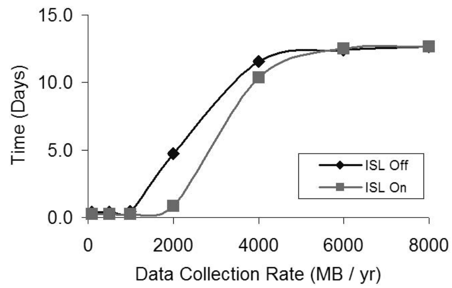

Figure 10. Average time with ISL on/off over data collection rate (Satellites 1 to 3 only)

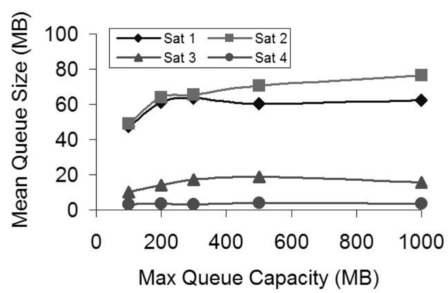

Figure 11. Mean queue size vs. max. capacity

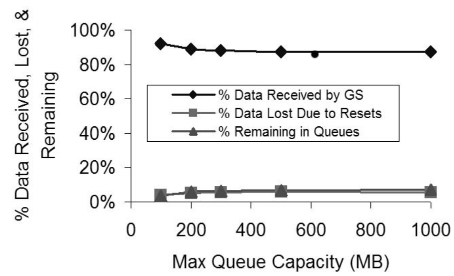

Figure 12. Data result vs. max. capacity

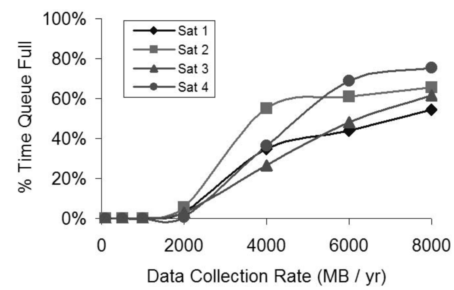

Figure 13. Filled queues vs. data coll. rate

work, because it generates data faster than it can transfer it to the ground with its one pass per day. With the network enabled, Satellites 1 and 2 assist Satellite 3, so the queue sizes balance and overall performance improves. Figure 10 shows the benefit that intersatellite communication provides as traffic (data collection rate) increases.

Varying maximum queue capacity Here, we increase the storage capacity of the satellites, so that they are able to collect more data. As shown in Figure 11, Satellites 1 and 2 have larger mean queues, because they act as an intermediate step to the ground for Satellites 3 and 4. The queue sizes increase somewhat as the maximum queue capacity increases to 200, but little benefit is seen above this point, since the extra space is not required. A drawback of larger storage capacity is that the percentage of data lost goes up because more data is discarded when a satellite resets (Figure 12). The amount of data collected increases slightly, but the actual amount of data received by the ground station remains constant, indicating that maximum network throughput has been achieved. Finally, the percentage of data reaching the ground station declines because a higher percentage of data is left in the queues or is lost due to resets.

It turns out that with larger queue sizes, our simple sample routing algorithm causes packets to transfer back and forth between satellites, unnecessarily wasting precious power. More bursty applications might benefit more from larger queue sizes. Larger queues allow more data buffering at the satellites and increase the effective transfer rate to the ground station. However, packets spend more time in the network, and satellite resets cause more data loss.

Varying data collection rate As the data collection rate increases, the percentage of time during which queues stay full increases (Figure 13). Note that the percentage of time queues are full increases quickly once the satellites collectively generate more data than they can transfer to the ground. Also note that the percentage of time that the satellite queues remain full converges at about 60%. Convergence occurs below 100% despite the fact that queues fill quickly, because satellite queues have no data after satellites fail, bringing down the average. Some data is also lost due to resets. Referring back to Figure 10 with three satellites, the average time that packets spend in the network grows with an increasing data collection rate, and peaks off as queues sizes peak.

Varying OrbComm rate Next, we evaluate network performance improvement in the presence of a commercial network like OrbComm. The OrbComm system provides continuous coverage and a lower communication delay, but it has some drawbacks. It transfers data much more slowly than other links (1000 MB/yr vs. 453000 MB/yr for the ground station), it uses more precious power per bit, and it has out-of-pocket costs associated with it. The OrbComm system reduces queue sizes (Figure 14), improving the sys-

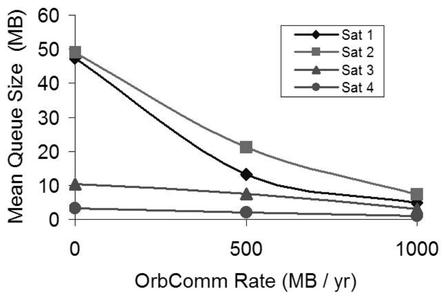

Figure 14. Mean queue size vs. OrbComm

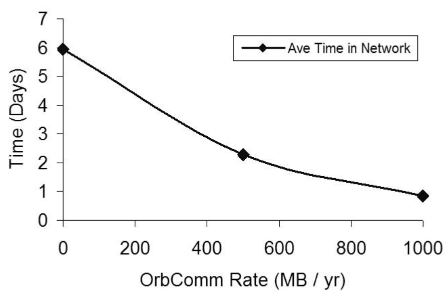

Figure 15. Average time vs. OrbComm rate

tem performance as a whole. As a result, the percentage of time that the queues spend filled drops, and the percentage of data lost due to resets decreases. The average time that packets spend in the network drops significantly (Figure 15). The OrbComm network may provide a good option for transferring critical time-sensitive command and telemetry information, since the packets it transfers benefit the most.

5. Conclusions

In this work, we evaluated the dependability of the ION satellite, which collects data for atmospheric measurements, and we performed studies aimed at improving the dependability of ION's successors. We also studied the dependability of a proposed LEO satellite network using IONs. More specifically, first we modeled an individual satellite and used analytical methods to explore the impact of radiation effects and component redundancy on single satellite dependability. Using the satellite model, we developed a satellite network model and used simulation to analyze the satellite network's dependability and performance. Our model was easily developed in Möbius and is flexible. For example, the model can support additional communications rules as the application requires. We could reduce data collection rates if satellite storage units begin to fill, or we could place multiple queues on each satellite with different quality-of-service levels. Finally, we could track and route packets individually with more sophisticated algorithms by using extended places with arrays for satellite queues. Overall, we gained valuable insights into extending the satellite's lifetime and building a satellite network to transfer scientific data to the ground.

6. Acknowledgments

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