TECHNICAL RESEARCH REPORT

Using Commercial Communication Satellite Constellations for Supporting Traffic from NASA Missions

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USING COMMERCIAL COMMUNICATION SATELLITE CONSTELLATIONS FOR SUPPORTING TRAFFIC FROM NASA MISSIONS

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ABSTRACT

NASA is interested in using commercial satellites to provide broadband communications support for the International Space Station and other space missions. We describe a large-scale simulation model that we plan to use for detailed performance studies of critical parameters such as QoS guarantees for specific services, traffic routing schemes, transport protocol support, dynamic bandwidth allocation methods, queuing disciplines, and handoff strategies. In this paper we focus on the unique challenges we face and how we plan to use simulations to investigate:

- the feasibility of using proposed commercial constellations to carry mission telemetry, command and control, and tele-science traffic between ground terminals and near-earth spacecraft.
- the end-to-end performance optimization of such systems.

1 INTRODUCTION

The deployment of the International Space Station (ISS) that started in November of 1998 has ushered a new era in space exploration. At the same time, advances in communications technology could allow investigators on Earth to enjoy a virtual presence on board the ISS[1]. In order to achieve this, there will be a need to provide high quality, broadband communications connectivity in order to enable cost effective global access to experimental data from the ISS and other space missions. NASA is also interested to gradually facilitate broadband Internet services throughout its missions, eventually leading to a scenario where every spacecraft and instrument in NASA's network can have an IP address and a connection to the Internet[2].

Gradual commercialization of space communications operations could enable:

- Reduction in cost for NASA's and ESA's broadband communication needs;
- Better, faster and easier dissemination of space mission and experimental data if some of the available bandwidth and global coverage of future commercial constellations can be utilized;
- Deployment of next generation commercial satellite constellations (since space agencies might become major customers);
- Faster development in the satellite industry and also enable other commercial entities to take part in experiments and development programs in space, such as future space habitats and planetary missions.

For these reasons we started an effort to investigate the use of next generation commercial satellite constellations for supporting broadband communications for the International Space Station (ISS). As a first step, we have developed a simulation model for this scenario, consisting of: the ISS, models of several commercial satellite constellations, the existing NASA Deep Space Network and the ground network of candidate commercial constellations. We consider this to be a minimal architecture, because all aspects of the model have been considered, including propagation characteristics, coverage aspects, traffic generation, node movement tracking, hand-off, and connectivity. This research work addresses the following topics:

- Determination, of particular traffic scenarios and QoS service requirements for an initial analysis scenario.
- Identification of potential commercial systems as

candidate for investigation, starting from simple GEO (existing) Ku/Ka-band systems and moving to the next generation Ka or V band MEO / LEO systems.

- Where necessary, application of analytical tools for traffic modeling, handoff analysis, fast end-to-end performance evaluation to derive performance bounds.

- Development of a detailed simulation model that includes network architecture & topology of Hybrid Network, and in particular:

- ISS (treated as an extremely LEO satellite) & ground network.

- Candidate Commercial Systems (constellation orbit model, ground network topology, information on routing options through constellation, Inter Satellite Links (ISLs) if any).

- Detailed simulation studies to quantify the performance of candidate satellite systems for specific services, protocols & traffic scenarios and recommend potential design modifications to ensure tele-science QoS requirements are met.

The performance parameters addressed include:

Coverage assessment: The purpose of this is to determine the maximum service time that can be made available to the ISS by the satellite constellation. (Percent of time that data could be transmitted to the ISS via the commercial satellite system - this includes Static & Dynamic coverage and the effect of Inter Satellite Links).

Throughput assessment: Maximum daily throughput depends on the availability duration (coverage statistics) and the per-channel data rate (link quality). Simultaneous data transmission on multiple channels must also be addressed in a complete model. Again, this must be specified in the ISS requirements for sending different data to different locations, and also to multicast or broadcast data to a number of locations.

QoS assessment: QoS is evaluated in terms of availability duration and link quality. Both quantities can be evaluated using the simulation model. Link quality is best described in terms of EIRP and G/T values that are specified in the ISS design and must be provided by the commercial constellation. Available duration can be computed based on the results of the coverage analysis.

Antennas & Terminals: Antenna & earth terminal characteristics with respect to required link quality are considered. It would be necessary to have an antenna design well suited for covering moving satellites(in the non-GEO case) and terrestrial traffic.

In this paper we describe a large-scale simulation model that we use and focus on the unique challenges we face and how we use simulation to investigate:

- the feasibility of using proposed commercial constellations to carry mission telemetry, command and control, and tele-science traffic between ground terminals and near-earth spacecraft.

- the end-to-end performance optimization of such systems.

2 COMMUNICATIONS SUPPORT FOR THE INTERNATIONAL SPACE STATION

2.1 Simulation Model

Our general model consists of the ISS (treated as a satellite in an extremely Low Orbit) with a network of three ground stations. We plan to incorporate along with that detailed models of several proposed constellations, and see how each one performs for specific traffic scenarios. To illustrate our modeling process we describe here two characteristic cases, focusing more on the more challenging MEO case:

- A system with three GEO satellites. This along with the ground network model makes up a basic network similar to NASA's current TDRSS-Deep Space Network (DSN).

- A system with 7 MEO satellites in a ring, based on the proposed Orblink MEO system [3].

ISS Module: The ISS is currently modeled as a simple traffic generator. After a random idle period, it creates a file whose size is uniformly distributed. The file is then divided into fixed-size packets that are created and transmitted deterministically. Destination addresses for each file are determined randomly from among the nine end-user terminal addresses. All packets within a file are sent to the same end terminal. No priority or service classes are implemented. The queue_sat module performs simple FIFO queuing, with a packet service time that is chosen to ensure proper flow control. There are infinite capacity transmit queues on ISS. Packets are transmitted only if the strength of the beacon signal received from any satellite is above a threshold value that is a simulation attribute.

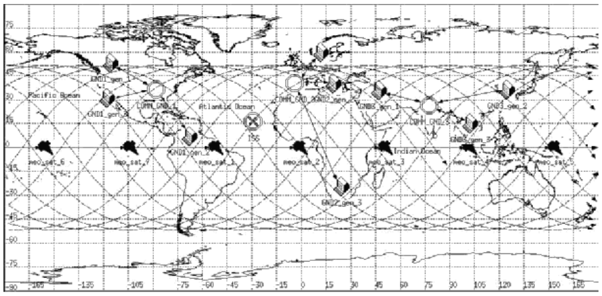


Fig 1. OPNET network model-MEO Case

2.1.1 Simulation Model Components-MEO Constellation

Continuous monitoring of beacon signal strengths from available satellites ensures correct operation of Pointing, Acquisition and Tracking (PAT) subsystem on-board the ISS, as shown in the node model. The ISS_beacon_tx module continuously broadcasts beacon signals to allow other nodes in the network to locate the ISS. Beacon signals that are received from the satellites are processed by the ISS_beacon_rx module. The seven radio receivers measure the signal strength that of the beacon that is received from each satellite. The result is made available to the queue_sat module to determine if the ISS can transmit packets.

The ISS-MEO handoff modules perform handover of the ISS transmit antenna. Based on the received signal strengths, the ISS_antenna_to_sat is handed off between satellites. Handoff on-board the ISS is performed as hard handoff (break-before-make).

ISS_once_proc is responsible for initializing state variables, model attributes and process attributes, and maintains the integrity of the node model over multiple simulation runs.

Moving the MAC layer to ATM will allow us to support multiple services in addition to the present file transfer (video, long-duration connections, multicast, high-priority data, etc). Protocol support at ISS will ensure that QoS requirements are met for each service type. Complex input traffic models will be used to model the distribution of different service applications.

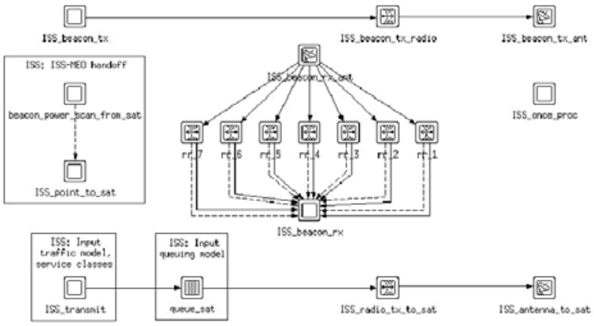


Figure 2 ISS Module

MEO Satellite Module: The MEO network is currently made up of 7 intelligent satellites, capable of OBP activity -- queuing, routing and handoff. Each satellite maintains continuous connections with its two adjacent satellites, and all 7 satellites form a ring in equatorial orbit at 9000 km. altitude. The meo_point_to_meo module checks and maintains the connections between adjacent satellites. Each MEO satellite has multiple transmit-receive pairs to adjacent satellites, the ISS, and the three ground stations. These tx-rx pairs are identified by the transmitter and receiver modules that feed into the queuing modules (rx_next_sat, rx_prev_sat, etc.) and receive data from the routing and processing module.

When a satellite receives a packet, it identifies it as belonging to commercial or ISS traffic. Commercial traffic is fed into the meo_pk_queue while traffic to or from the ISS is received in the iss_pk_queue. A FIFO queuing discipline is used in both queuing modules, because the generated traffic from commercial end stations and the ISS are composed of a single priority class. Additions to this model will include a priority-based queuing scheme based on QoS specifications for packet streams.

The meo_proc processing module then performs shortest-path routing and forwards the packet to next-hop satellite or destination ground station. This is done based on the value in the “destination address” (see Packet Formats section) field. From the destination address of the end-user terminal, the satellite determines the closest ground station to the terminal. Continuous location monitoring allows the satellite to know if it is currently in line-of-sight of the destination ground gateway. If so, the satellite downloads the packet to the destination ground gateway. Otherwise, it forwards the packet to one of its neighboring satellites based on Dijkstra’s shortest-path algorithm, or destroys the packet if its lifetime is exceeded. The operations that every satellite node performs include MAC-layer echo cancellation, address resolution, hop-count based lifetime control, and shortest-path routing.

The PAT subsystem performs continuous monitoring of ISS beacon signal and beacons from three GND stations to ensure correct operation. The beacon_tx_proc module on each satellite continuously transmits low bit rate beacon packets to the ground gateways and to the ISS. Beacon signals that are received from the ISS and each of the three ground gateways is analyzed for signal strength. The MEO-GND handoff subsystem monitors the signal strengths and implements hard handoff between GND stations.

Once_proc is responsible for initializing state variables, model attributes and process attributes, and maintains the integrity of the node model over multiple simulation runs. Once the satellites are modeled as ATM switches, IP protocol implementation at satellite nodes allows us to perform IP-level routing. The IP-over-ATM problem is already a well-known problem with many research efforts addressing various parts of the problem. At satellite nodes, IP will be limited to IP-routing component. No ARP is recommended over the satellite network, and IP-Encapsulation is not needed because the network layer is highest layer at the MEOs.

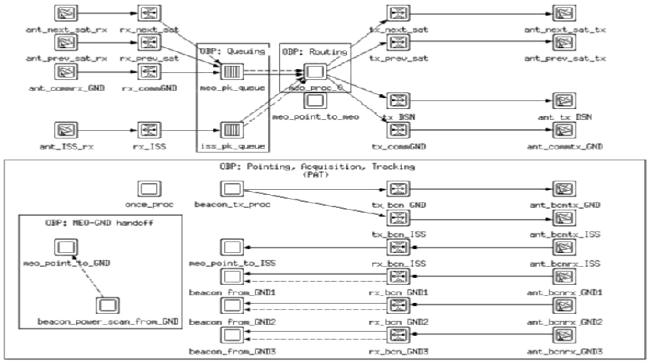


Figure 3 MEO Satellite Module

Ground Station Module: The simulation model currently has 3 ground stations that continuously monitor the movement of the MEO satellites to ensure correct PAT operation. Each GND station receives, from ground terminals, commercial traffic to be transmitted over satellite to other ground terminals. It also receives ISS traffic to be transmitted to ISS. GND stations also receive return traffic from the MEO network that is made up of ISS and commercial traffic. These packets are received by the sink_rr receiver module. Received packets are queued at the sink_queue to be transmitted to end-users. The sink processing module uses an impartial FIFO de-queuing scheme to remove received packets from the queue and send them to one of the three end-user terminals based on the packet's destination address. All three end terminals are connected to the ground gateway using point-to-point links (pt_0, pt_1, pt_2).

Point-to-point links are also used to receive data packets from the end terminals. A simple queuing model is implemented at present, with intelligence to initiate high data rate transfer of queued packets to satellite during periods of visibility. The bandwidth is shared equally between ISS packets and commercial packets in the commGND_queue module. The commGND_to_sat module periodically checks for LoS to any satellite and initiates high rate transfer from the queue to the satellite.

GND_beacon_tx and GND_beacon_rx modules are responsible for the background beacon tracking operation to ensure that minimal number of data packets are lost due to small and rapidly-changing LoS windows at the ground gateway. The beacon mechanism logically links the ground gateway network with the MEO satellite network.

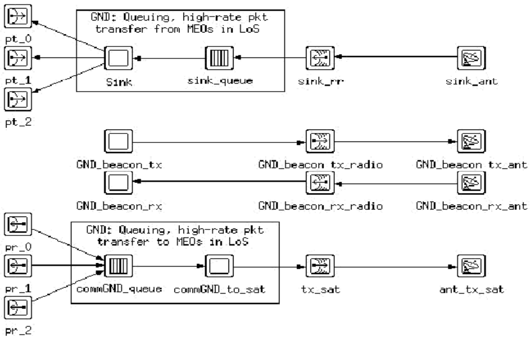


Fig 4. Node model for GND station

Advanced bandwidth allocation and queuing models can be used to partition available bandwidth between commercial traffic and ISS traffic, with the partition scheme being a test case.

Ground Terminal/Network Gateway Module: The network model shows 9 ground terminals that are connected to the 3 GND stations (three to each).

These terminals can be considered to be network gateways to corporate/local/wide-area networks. Each terminal acts as a source and sink for data traffic to/from other terminals and to/from the ISS. The modules GND_gen and Sink perform these functions at the network end-user terminals.

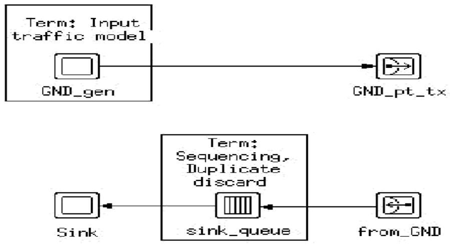


Fig 5 Model for ground terminal/network gateway

A simple FIFO transmit queue is shared by both types of traffic. The receiver queue at network gateways performs segmentation/reassembly, MAC-layer packet sequencing, and duplicate packet detection and discarding. SAR operations are performed based on the packet's sequence number. Packet sequencing operations are carried out using an internal queue called the overflow queue, which stores packets that are received out of order. If a packet's sequence number is less than expected, it is discarded as a duplicate. If the sequence number is greater than expected, it is inserted into the overflow queue and the queue is sorted using a bubble-sort technique. The head of the overflow queue is then checked to see if it is the packet with the expected sequence number. This operation is performed in the sink_queue process model.

Improved traffic models are planned at transmitters to model multiple traffic types for different service classes and QoS requirements. IP (or other network-layer) protocol and basic TCP implementation to provide support for end-to-end QoS guarantees for multiple services. All three IP components (IP-ARP, IP-Encapsulation and IP-Routing) will be implemented. End-to-end statistic collection, average packet delays, packet loss, queue lengths, performance for each service class and traffic type.

2.1.2 Simulation Model Components-GEO Constellation

In this case, model consists of similar four types of Modules described earlier. Satellite Module of GEO case however is much simpler as the network topology is very simple.

2.2 Preliminary Results & Discussion

Since we are dealing with a preliminary model at this early stage, we are not yet able to run detailed end-to-end performance simulation runs, so the information we can get a this stage is limited. However, we are currently able to look at some proof of concept runs and verify the correct operation of the different components in the network.

Fig. 6 plots the average queuing delay at each GND station. Fig. 7, plots the queue length over a fixed time interval over selected satellites. It shows the variation in load of each satellite. Note that the load on each satellite in this simulation model will converge to the mean over multiple revolutions. Over a single revolution the values will not converge, as the orbital period of the ISS is not a multiple of the orbital period of the MEO network.

2.3 Coverage Analysis

We next turn or attention on some preliminary coverage analysis for two different constellations, using Orblink as the example for the MEO case and Spaceway [4] as the example for a next generation GEO commercial system. The following assumptions apply to the two scenarios we investigate, using the STK package. Note that these are simplifying assumptions to provide an initial frame-of-reference and do not represent the particular details of the system design for the two constellations, since much of that information is not available in the public domain:

- Satellite antenna is fixed (pointing nadir), and 90-deg cone angle
- Line-of-sight is assumed for access at the satellites (no elevation angle or other constraints are placed on the satellites)
- "complete chain access" means the total time during which any object within the first element in the chain has access to any object in the next and sequential elements in the chain.

We consider two scenarios:

2.3.1 Scenario 1 (Fixed ground antennas, variable cone angle)

- Fixed ground antennas (north-pointing)

- Variable cone angle
- Fixed elevation angle
- Fixed satellite antennas

This scenario assumes that the antenna's position on the ground station is fixed, pointing local vertical north (90-deg elevation). The size of the cone would be the determining factor for duration of access in this case. However, if an additional constraint was point on the antenna such as minimum elevation angle of the access, then this could impact the access time if the elevation angle enters within the mounds of the cone. So, this scenario assumes that the minimum elevation angle constraint is smaller than the complement of the cone half-angle. The data used is given in *Table 1*.

Cone Angle, C	ISS-SW-GN	ISS-SW-WALLOPS	ISS-OL-GN	ISS-OL-WALLOPS
5	0	0	0	0
10	0	0	0	0
20	0	0	0	0
35	0	0	0	0
50	0	0	0	0
60	79856	61843	15397	15397

TABLE 1: Fixed Antenna, Fixed Elev.Angle (e<90-c);Variable Cone Angle

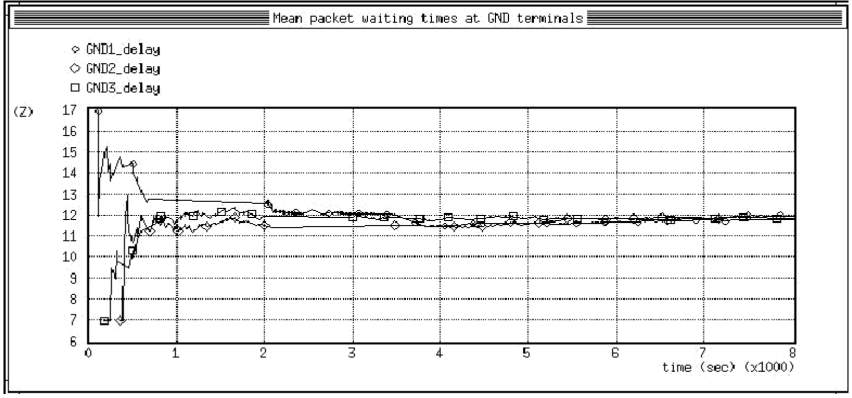


Fig. 6 Average RX-Queueing Delay at GND stations

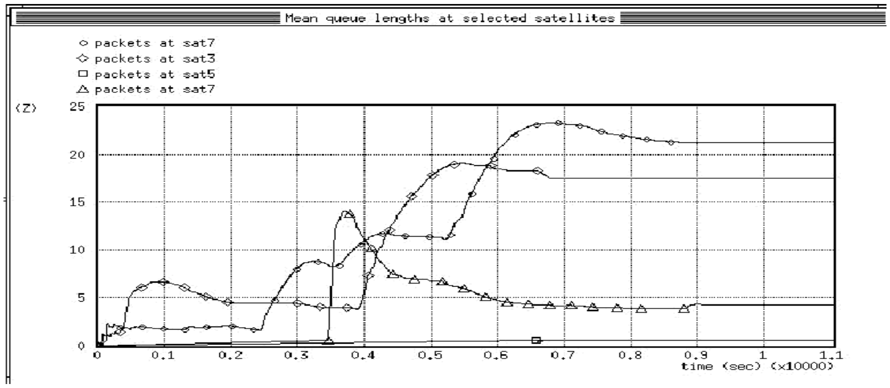


Fig 7. Average OBP-queue lengths at MEO satellites

It is interesting to note that in this case, the duration exhibited is similar to that of a step function – there is no complete chain access at all unless the cone angle on the fixed ground antenna is greater than a certain amount. This occurs because all the ground stations are at high latitudes, while both constellations have equatorial orbits (zero degree inclination). A report of the elevation angle of line-of-sight access from the ground station closest to the equator, Wallops, to the Spaceway constellation is about 38.1 deg. This means that if the antenna was north-fixed, the minimum half-cone angle needed for even the best-located facility would be 90 -38.6 = 51.4 deg. The minimum half-cone angle needed for the best-located facility to access orblink is 90 - 31.4 = 58.6 deg. In general, satellites at greater altitudes (such as Spaceway) have less geometric constraints than those at lower altitudes (such as Orblink).

2.3.2 Scenario 2 (Tracking antennas, variable elevation angle)

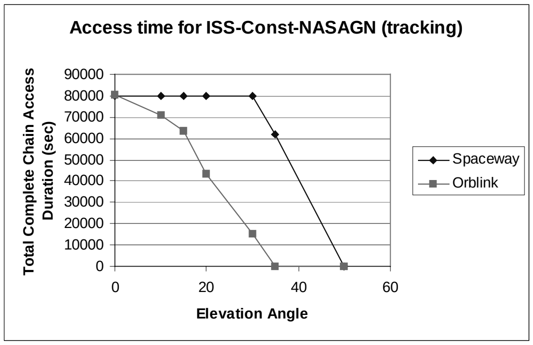
Tracking ground antennas (targeted on constellation)

- Variable elevation angle
- Fixed cone angle
- Fixed satellite antennas

Elev Angle, e	ISS-SW-GN	ISS-SW-WALLOPS	ISS-OL-GN	ISS-OL-WALLOPS
0	79856.71	61483.33	80418.19	55219.20
10	79856.710	61483.33	70889.31	48852.77
15	79856.71	61483.33	63566.43	44964.2
20	79856.71	61483.33	43534.15	41463.08
30	79856.71	61483.33	15397.08	15397.09
35	61843.327	61483.33	0	0
50	0	0	0	0

TABLE 2: Tracking Antenna, Fixed Cone.Angle (5 deg min); Variable Elevation Angle

For the case in which the antennas on the ground station are allowed to rotate and track the commercial satellite during the period which there is acquisition, the antenna by definition moves as to maintain the satellite along the boresight of the antenna. In this situation, the cone angle of the ground antenna is not important; for as long as the center of the antenna has line of sight to the satellite, there is contact. The minimum allowable elevation angle, however, will directly restrict the amount of access obtained. In this scenario, the minimum elevation angle constraint will be varied from 0 to 50 deg. (*Table 2*).



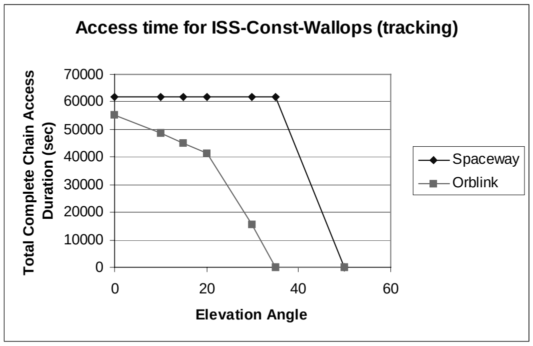


Figure 8 Access Time Duration Vs Elevation Angle

As can be seen from the graphs and as discussed earlier, constellations with higher altitude will generally have better coverage. In this case, the distribution of the facilities were such that the total duration did not vary until a certain elevation angle, at which the duration drastically drops. We see the interesting properties of having two constellations that are both equatorial, but differ by altitude.

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3 COMMUNICATION SUPPORT FOR OTHER NEAR-EARTH MISSIONS

The ISS is the top priority NASA mission at the moment, and the one with the greatest demandfor broadband communication support. However, a number of other near-earth missions need to be supported as well, with varying coverage and data requirements. We next turn our attention on an initial study on the coverage issues that need to be addressed in these cases. We study examples of missions in various altitudes and inclinations, and investigate the use of three proposed satellite constellations for this purpose. It is important to note that these represent the final implementations of the complete constellations as they were described in recent FCC filings. These systems are under development and are undergoing significant changes, and will probably be implemented in several phases. The analysis presented here is only used to demonstrate the methodology and a frame of reference; a detailed modeling of a lot of proprietary details of the final designs needs to be used for a precise and more realistic evaluation of the suitability of these systems for this service. We also like to point out that systems that reach an arrangement with NASA to support mission communications will probably accommodate design modifications that would allow them to focus on this task and meet the required quality of service and coverage. The commercial systems considered here are:

Spaceway: The Spaceway constellation consists of 20 geo-synchronous satellites at 15 positions. For the sake of this analysis, this system is represented with 15 satellites with one at each of the longitudinal positions: 101º W, 99º W, 67º W, 49º W, 25º E, 36º E, 41º E, 48º E, 54º E, 101º E, 132º E, 149º E, 164º E, and 173º E. The constellation is designed to provide coverage over populated land areas, so the longitudinal positions of the satellites are not evenly distributed, and instead are chosen to provide more land coverage.

The instruments on the satellites in actuality consist of 183 spot beams with a 1.5º field-of-view per beam. Because each satellite is stationary relative to the earth, each beam can be individually pointed to target certain areas on the earth. Because information on the pointing of each individual beam is currently not known, we approximate the them with one conic sensor on each satellite with a 7º half-cone angle pointing nadir (towards the center of the earth).

Astrolink: The Astrolink constellation consists of 9 geo-stationary satellites in 5 orbital positions, at 97º W, 21.5º W, 130º E, 2º E, and 175º E. For this analysis, the only the satellites with the 5 unique orbital positions were used. The antenna is assumed to have a 5º half cone angle pointing fixed at the center of the earth.

Orblink: The Orblink constellation consists of 7 satellites at an altitude of 9,000 km following an equatorial orbit (zero degree inclination). This constellation is approximated in this analysis with an even distribution of satellites around the equator. The antenna on each satellite is assumed to have a 24º half-cone angle pointed fixed towards the center of the earth.

3.1 Static Coverage Analysis

For each satellite constellation, static coverage analysis was performed by fixing an arbitrary moment in time, and determining the percentage of the earth that has access to one or more of the commercial satellites. This analysis was then repeated for space mission altitudes of 300 km and 700 km. Generally, reduction in percentage of coverage is seen with increasing altitude. Commercial constellations that are low in altitude (such as Orblink) will usually be more susceptible to changes in the NASA user's altitude than constellations higher in altitude. Figure 9 shows the changes in coverage for the Orblink example, for three different mission altitudes.

3.2 Dynamic Coverage Analysis

This analysis shows the dynamic geometric coverage as the NASA user satellite and commercial satellite constellation are both moving over a period of time. Results are obtained by running the scenario for a 10-day period at 60-second step sizes. One continuous coverage is defined as the period of time that the NASA satellite is in field-of-view with one or more of the sensors on the commercial satellites. Repeated trials were performed for each commercial constellation, with varying cases for the NASA user satellite. Results are listed in Table 3.

Figure 10 shows an example of the type of analysis of these results we can use to determine percentage of coverage and the effect of the mission altitude and inclination angle on coverage by the three constellatons. Thesecould then be translated to type of services that can be supported and maximum durations of these services, based on the coverage duration, as well as scheduling of services based on the mission location with respect to the satellite constellation and the ground.

SPACEWAY Parameter	**Case 1: 300 km, 28.5 deg**	**Case 2: 500 km, 28.5 deg**	**Case 3: 700 km, 28.5 deg**	**Case 4: 500 km, 57 deg**	**Case 5: 700 km, 98.2 deg**	**Case 6: 400 km, 51.5 deg**
Coverage Percent	90.8	88.3	85.9	47.9	36.4	55.5
Coverage Time	13081	12709	12367	6892	5243	7986.8
Continuous coverage, ave (min)	46.6	44.4	45.5	21.9	19.5	23
Continuous coverage, max (min)	91.2	57.5	59.1	27.3	22	30.4
ORBLINK Parameter						
Coverage Percent	100	100	100	54.1	39.7	64.7
Coverage Time	14400	14400	14400	7793	5720	9321
Continuous coverage, ave (min)	14400	14400	14400	25.6	19.6	29.7
Continuous coverage, max (min)	14400	14400	14400	27	20.8	31.6
ASTROLINK Parameter						
Coverage Percent	45.4	40.5	36.9	19.6	15.3	22.2
Coverage Time	6545	5833	5317	2828	2203	3191
Continuous coverage, ave (min)	12.1	12.9	13.5	12.8	11.8	13
Continuous coverage, max (min)	24.5	25	25.5	17.1	14.2	18.8

Table 3

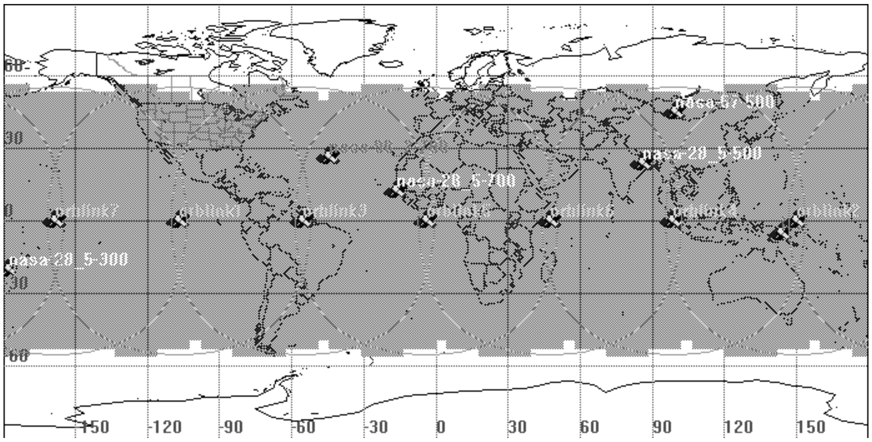

Figure 9a Orblink Static Coverage for mission at 0 km (80%)

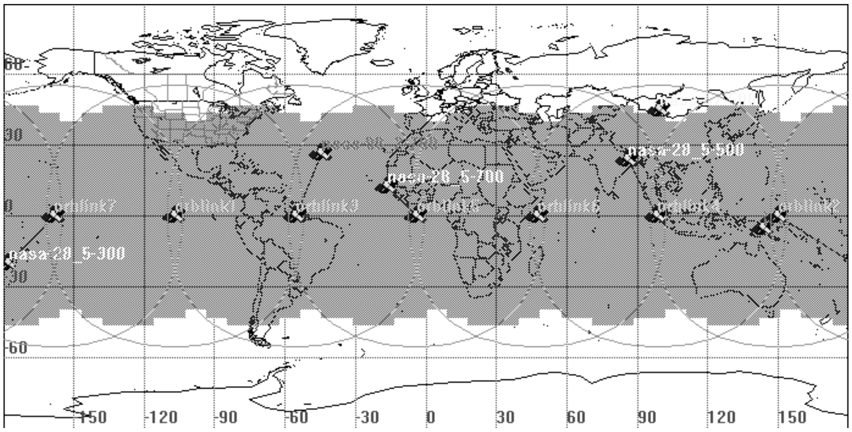

Figure 9b Orblink Static Coverage for mission at 300 km (68.6%)

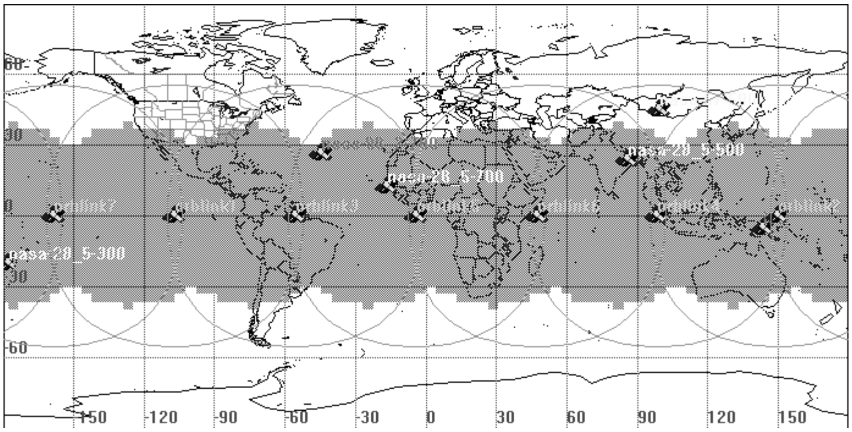

Figure 9c Orblink Static Coverage for mission at 700 km (57.9 %)

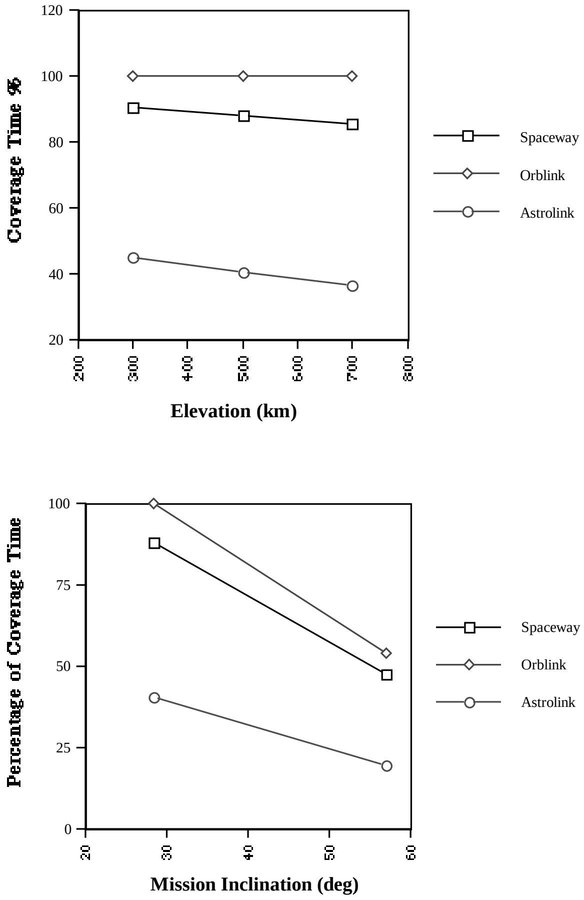

Figure 10 Effect of mission altitude(elevation) and inclination on coverage

4 SUMMARY & FURTHER WORK

We are developing a methodology and a large-scale simulation model to evaluate the feasibility of carrying NASA mission payload, command and control, real-time and low-priority data between ground user terminals and near-earth spacecraft, using proposed commercial satellite constellations. The simulation model will allow us to perform detailed studies to quantify the performance of satellite systems for the following test parameters: specific services and their QoS requirements, protocols, traffic models, satellite routing schemes, on-board bandwidth/buffer allocation methods, queuing disciplines, and handoff strategies.

We have explained some of the features of the present models. Test modules will next be developed independently, to simulate the operation of each test case bandwidth assignment algorithms, routing algorithms, coverage issues and handoff schemes. This will enable us quantify and analyze the end-to-end performance for specific data services. The next two major steps in this work will be in modelling the data services and statistics of the traffic that must be supported as well as the protocol modifications that will allow these services to be supported.

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