Orbit Design Based on the Global Maps of Telecom Metrics ©📖✓

Charles H. Lee[1], Kar-Ming Cheung, Chad Edwards, Gary K. Noreen and Arvydas Vaisnys
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109
818-393-0662
Charleshlee@fullerton.edu
Kar-Ming.Cheung@jpl.nasa.gov
Chad.EdwardsCheung@jpl.nasa.gov
Gary.K.Noreen@jpl.nasa.gov
Vaisnys@jpl.nasa.gov

Abstract— In this paper we describe an orbit design aide tool, called Telecom Orbit Analysis and Simulation Tool (TOAST). Although it can be used for studying and selecting orbits for any planet, we solely concentrate on its use for Mars. By specifying the six orbital elements for an orbit, a time frame of interest, a horizon mask angle, and some telecom parameters such as the transmitting power, frequency, antenna gains, antenna losses, link margin, received threshold powers for the rates, etc. this tool enables the user to view the animation of the orbit in two- and three-dimensional different telecom metrics at any point on the Mars, namely the global planetary map. Particular metrics include the (i) number of contacts, (ii) total contact duration, (iii) maximum communication gap, (iv) maximum supportable rate (v) return data volume at a best single rate or with an adaptive rate, along with the (vi) orbiter's footprint, and (vii) the local solar times. Unlike other existing tools, which provide mostly geometry and the view periods for the orbiter and a single location on the planet, our tool incorporates the link analysis to generate the telecom performance metrics for the entire planet. The added capabilities allow the user the extra degree of freedom in deciding the orbit and focusing on meeting specific mission requirements such as what type of supportable data rates can be closed, how much the data throughput are expected, and how long the time gap is between communication periods. Direct applicability of our tool is the 2009 Mars Telecom Orbiter mission. The telecom predicts generated by our tool for different candidates lay the foundation that can be use for selecting the final orbit. Numerical simulations and telecom predicts for five different candidate orbits will be also presented.

Table of Contents

1. INTRODUCTION
2. TELECOM ORBITAL ANALYSIS & SIMULATION TOOL (TOAST)
3. GLOBAL MAPS OF CONTACT & TELECOM METRICS
4. SAMPLE MTO ORBITAL CANDIDATES & METRICS
5. SUMMARY
6. REFERENCES
7. BIOGRAPHY

1. INTRODUCTION

The success of large data volume return from the 2004 Spirit and Opportunity rovers relayed through the Mars Global Surveyor and Mars Odyssey orbiters has proven the significance of having a dedicated telecommunication orbiter in the Mars Network and infrastructure. As part of NASA's plan, the Mars Telecom Orbiter (MTO) will be the mission to fulfill such role and the deployment of such orbiting element would broaden the infrastructure on Mars by many folds including the capabilities to demonstrate new advanced technologies such as Optical Communications, Precision Rendezvous and Autonomous Navigation, high-power Ka-band power amplifiers communication, etc.

MTO will be launched in the later part of 2009 and will begin its service 2010. Its service life is expected to last between six years to a decade. Because its telecom capabilities substantially exceed those provided by its predecessors (Mars Global Surveyor, Odyssey, Mars Express, Mars Reconnaissance Orbiter), MTO will, in addition to performing its own science agenda, (i) provide faster data relay services at larger data throughputs for

© 0-7803-7231-X/04/$17.00/© 2004 IEEE
📖 IEEE Aerospace Conference 2004 Paper No. 1376;
✓ The work in this article was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
[1] Charles H. Lee is a JPL faculty-part-time researcher from the Department of Mathematics at California State University Fullerton

future and existing science missions operating on the Martian surface, in the Martian atmosphere, and in orbit, (ii) provide critical events coverage such as entry-descent-landing and In-Situ experiments, and (iii) enhance the success for future Mars sample-return missions. As a result, selecting a service orbit is an extremely important task.

There are many technical challenges associated with selecting such dedicated telecommunication orbiter; however, the following ones deserve serious considerations. Namely, through the different phases of its six- to ten-year lifetime, MTO has to provide the relay service to multiple missions ranging from Mars Scout-class landers, aero-balloons, aero-gliders to Mars rovers and orbiters. Although the missions that MTO will serve in the future are known, they are not well defined yet at time of MTO development. Thus it is necessary that MTO can provide global access to any location on Mars. Further, MTO also has to *be at the right place the right time* to provide critical event coverage. Of course, MTO has the capability to maneuver its orbit to tailor its service to other missions, but its Delta-V fuel is limited by its own payload and only moderate changes to its size, shape, and inclination can be assumed. Selecting the optimal orbit for MTO is a challenge in the sense that its initial orbit, the subsequent precessing orbit, and the orbit due to controlled maneuvers must provide sufficient coverage needs to its customers, satisfy the telecom requirements of the missions, while meet its own constraints.

2. Telecom Orbital Analysis & Simulation Tool

Our primary goal in this paper is to develop an orbit design aide tool, called the Telecom Orbital Analysis and Simulation Tool (TOAST), which provides the necessary metrics to facilitate the orbit selection process. MATLAB is the only software required to run TOAST, so it can be ported over different platforms such PCs, Unix, and Linux. It can also be set up as a web server application where any user with appropriate authorization can have access via an internet browser to run its latest models. It should be remarked here that although it is currently set up for Mars missions, some modifications can be made to allow the flexibility to extend its capabilities to other planets, rendering its capability to extend its current existence to missions such as the Lunar Orbiter missions and the Jupiter Icy Moon Orbiter (JIMO).

TOAST takes into account the planetary oblateness (J2 constant) to calculate the dynamics of the orbiter [1, 2]. It also provides the means for orbit visualization such as footprints, antenna coverage, and animation in two-dimensional (Figure 1) and three-dimensional (Figure 2) space. The user can compute solely the contact between the orbiter and a specific point (Figure 1 and 2) on the Martian surface or compute the global map of contact for the entire Martian surface (discussed in Section 3).

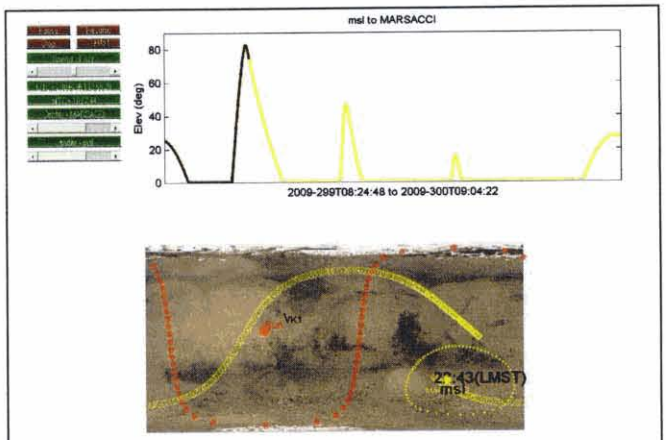

Figure 1. TOAST 2D Animation & its contact with a point on the Martian surface

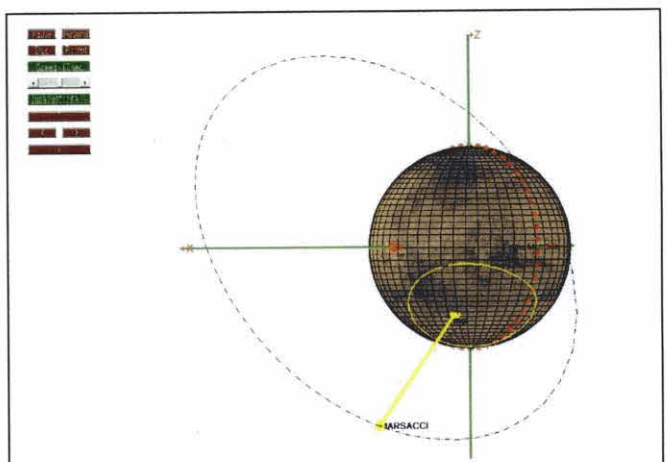

Figure 2. TOAST 3D Animation & its contact with a point on the Martian surface

The other significant advantage in using TOAST is its capability to provide the telecom performance for the orbiter with the Martian surface. TOAST can allow the user to input telecom parameters ranging from very early stage of the mission such as transmitting receiving power, gain, loss, supportable rates, link margin, frequency band, etc. to later development of the mission such as antenna pattern, system noise model, polarization loss, etc. TOAST in return lets the user know on the Martian surface, for example, what the largest data rate the orbiter link can close, how much data volume for different frequency bands can a certain region return through the relay link, etc. These telecom metrics will be discussed in more detail in Section 3.

3. Global Maps of Contact & Telecom Metrics

To provide the comprehensive evaluation and comparison for the different candidates, TOAST provides two types of global maps; the contact metrics and the telecom metrics.

In terms of the contact metrics, depending on the horizon mask angle, TOAST can provide the following sample global maps for the Martian surface:

(i) **Number of Contacts per Sol:** This number is often an important requirement for a landing asset. For instance, a morning pass and an afternoon pass are normally used by the Spirit and Opportunity rovers.
(ii) **Cumulative Contact Hours per Sol:** Uniform cumulative contact hours are preferred for the different orbits as the future landing assets are not known at the time of MTO development.
(iii) **Longest gap between communications:** This is one of the most critical metrics because it can provide minimum time one should expect until the next contact should the landing asset is in the safe mode.

Particular telecom metrics of important to the missions that TOAST can provide include:

(i) **Maximum Supportable Data Rates:** The dynamics of the range of the orbiter can dictate what data rates can be closed for the different regions on the Martian surface. Orbits with high supportable rates with the global maps that spread uniformly for all longitudes and latitudes are preferred.
(ii) **Return Data Volumes:** this type of global maps provides the return data volumes for different frequency bands and different types of processing rates such as a single optimal data rate or multiple adaptive data rates for a pass.

4. Sample MTO Orbital Candidates and Metrics

Numerous potential candidates for its orbit have been considered. The criteria for considerations include the following characteristics. High altitude or large semi-major axis orbits are preferred to allow longer pass durations and larger footprints. This is ideal, especially for critical event coverage. Although circular orbits are preferred to maintain constant range and constant footprint sizes, elliptical orbits are also considered because they generally require less Delta-V fuel. Sun-synchronous orbits are also considered because they can provide consistent illumination, can save spacecraft power, and can reduce system heat. To guarantee global access for any surface element on Mars, intermediately inclined orbits are included. Particular attention is also paid to the repeating ground track orbits due to their constant contacts with any point on the surface every sol. When superimposing the Sun-synchronous criterion with the repeating ground track and stationary periapse, a special type of orbits is formed. These orbits will passes over the any point on Mars surface the same Local Mean Solar Time (LMST) each sol.

To demonstrate the comparisons between the orbital candidates, the following four among forty candidates are considered in this paper:

(i) **CSS4450N** Circular Sun Synchronous Orbit with 4450-km altitude
(ii) **MACCI4N** Critically Inclined Repeating Ground Track with Four Orbits Per Sol and Stationary Periapse
(iii) **CSS4N** Circular Sun Synchronous Orbit with Repeating Ground Track with Four Orbits Per Sol
(iv) **ESS4N** Elliptical Sun Synchronous Orbit with Repeating Ground Track with Four Orbits Per Sol

The orbital elements and the types of orbits are shown in Table-1. All considered orbits are assumed to approach Mars from the Northern pole. The horizon mask angle for the Martian surface is assumed at 10 degrees and the simulation time for the orbits is one Martian Sol (88775.244 seconds). The resolution for the global maps is at 1 degree for both the longitude and the latitude.

The telecom assumptions for the UHF and X-band frequencies are described in Tables 2 and 3. Mainly they contain simple telecom parameters such as the transmitting power gain and loss and the receiving gain and loss, plus the link margin.

Table 1: Six orbital elements and orbit types for the MTO's candidates

	CSS4450N	MACCI4N	CCS4N	ESS4N
Semi-major axis (km)	7846.2	8114.8	8118	8117.188
Eccentricity	0	0.464	0	0.2
Inclination	130.2	116.565	136.683	132.152
Ascending Node	278.949	278.337	278.450	278.949
Argument of Perigee	137.169	132.610	134.046	137.169
Epoch at Perigee	16 Oct 2010 19:22:16	13 Oct 2010 23:33:08	17 Oct 2010 02:44:15	15 Oct 2010 07:02:15
Circular/Elliptical	Circular	Elliptical	Circular	Elliptical
Sun Synchronous	Yes	Yes	Yes	Yes
Repeating GT	No	Yes	Yes	Yes
Stationary Periapse	No	Yes	No	No

Table 4 shows MTO's received power thresholds and the corresponding supportable data rates.

Table 2: Telecom Assumptions for the UHF-Band

Xmt Power	10	(W)
Xmt Antenna Gain	0	(dBiC)
Rcv Gain	15	(dBiC)
Frequency	401.5	(Mhz)
Margin	6	(dB)

Table 3: Telecom Assumptions for the X-Band

Xmt Power	15	(W)
Xmt Antenna Gain	24	(dBiC)
Rcv Gain	24	(dBiC)
Frequency	8450	(Mhz)
Margin	3	(dB)

Table 4: Received Power Thresholds & Supportable Rates

Threshold Power (dBm) at Input to the Electra Transceiver			
0 dB Margin, 90 deg Mod Index, QPSK, Full Duplex			
Nominal Filter Losses and NF, Mars Sky Temp = 190 Kelvin			
Symbol	Coding (K=7, R=1/2)+(255,239) RS	Data	Threshold Power (dBm)
Rate (sps)	No Interleaving Prox-1 (FER 1e-3)	Rate (bps)	Input to Antenna Connector
1,000	Yes	937	-135.5
2,000	Yes	1,875	-132.5
4,000	Yes	3,749	-129.5
8,000	Yes	7,498	-126.5
16,000	Yes	14,996	-123.5
32,000	Yes	29,992	-120.5
64,000	Yes	59,984	-117.5
128,000	Yes	119,969	-114.5
256,000	Yes	239,937	-111.5
512,000	Yes	479,875	-108.4
1,024,000	Yes	959,749	-105.0
2,048,000	Yes	1,919,498	-101.3
4,096,000	Yes	3,838,996	-97.7
4,096,000	No Coding	8,192,000	-86.8

Each of the Figures 3-9 has four subplots for the four orbital candidates respectively with the CSS4N orbit in the upper left (UL) corner, the CSS4450N orbit in the (UR) corner, the ESS4N in the lower left (LL) corner, and the MACCI4N in the lower right (LR) corner.

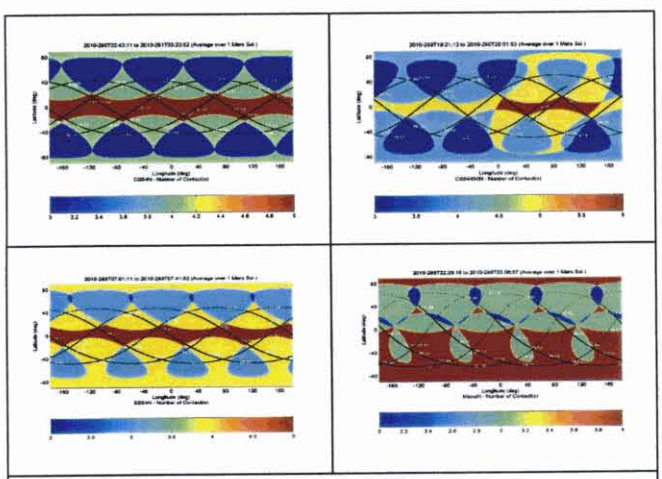

Figure 3. Number of Contacts
CCS4N(UL)-CSS4450N(UR)-ESS4N(LL)-MACCI4N(LR)

The selected orbits have relatively the semi-major axes and the orbital periods are a quarter of a sol except the CSS4450N orbit, which is relatively shorter. Figure 3 and Figure 4 display the number of contacts and the cumulative time of contact respectively. It can be seen from Figures 3 and 4 that circular orbits provide a more evenly coverage for the hemispheres. Due to their northern approach (periapse), the elliptical orbits favor the southern more as the passes are much longer. In addition, some areas in the northern hemispheres (10N-80N) can suffer from 12 to 18 hours of communication gap to elliptical orbits, whereas the circular orbits suffer at most 13 hours of communication gap (see Figure 5).

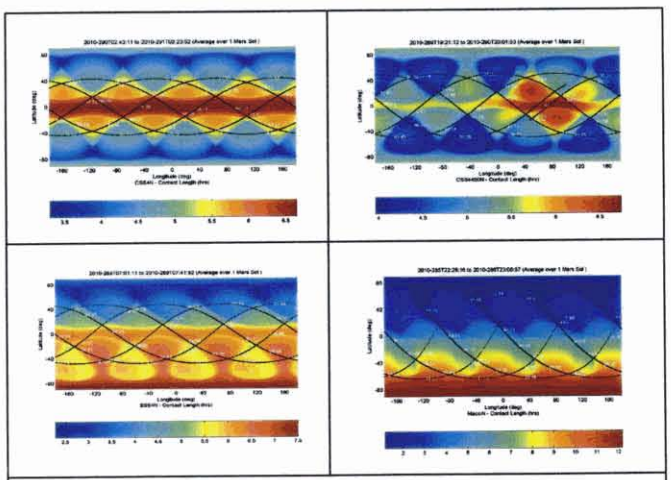

Figure 4. Hours of Contact
CCS4N(UL)-CSS4450N(UR)-ESS4N(LL)-MACCI4N(LR)

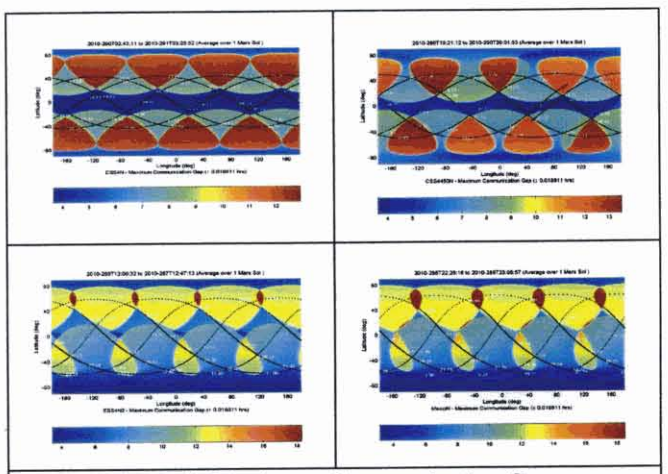

Figure 5. Maximum Communication Gaps
CCS4N(UL)-CSS4450N(UR)-ESS4N(LL)-MACCI4N(LR)

Figure 6 and Figure 7 show the global maps of the maximum supportable rates for the UHF and X bands respectively. Again as expected, the data rates are more uniform for circular orbits; whereas those for the elliptical orbits vary significantly. The rates at or near periapse are up to eight times faster than those near the apoapse depending on the eccentricity. On the other hand, passes at or near the apoapse are quite significantly longer. Thus the global maps for the data volume may be a more appropriate metric and Figures 8 and 9 depict the return data volume for the UHF and X-band respectively. The return data volumes for the UHF band are computed as follows. Though several rates are possible during a pass, a

single best rate is chosen based on the largest possible return data. This is a typical scenario for MER-class landing assets. For a more advanced future Martian landing asset, the received data rates can be adaptive throughout the pass, which is the assumption we employed in computing the return data volume for the X-band in Figure 9.

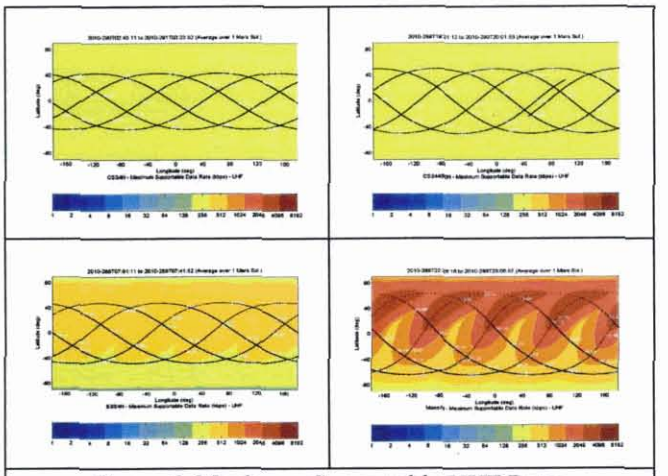

Figure 6. Maximum Supportable UHF Rates CCS4N(UL)-CSS4450N(UR)-ESS4N(LL)-MACCI4N(LR)

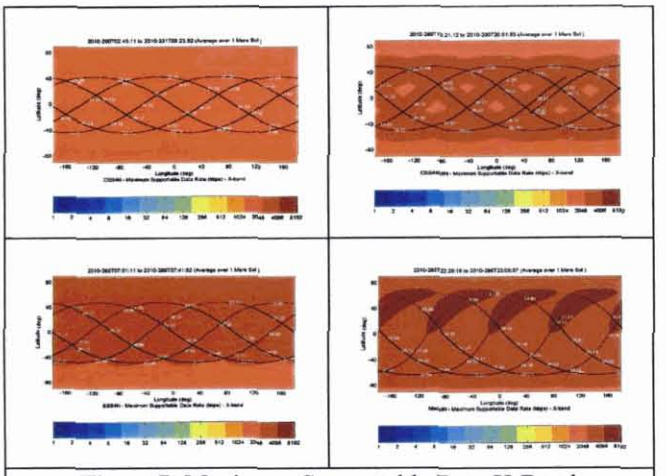

Figure 7. Maximum Supportable Rate X-Band CCS4N(UL)-CSS4450N(UR)-ESS4N(LL)-MACCI4N(LR)

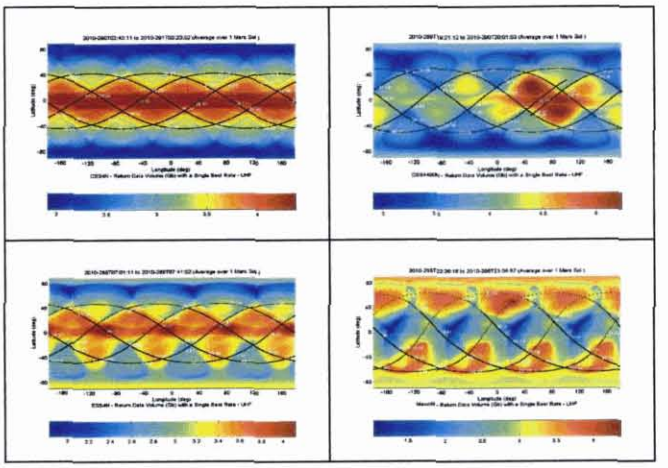

Figure 8. Return Data Volume UHF – Best Single Rate CCS4N(UL)-CSS4450N(UR)-ESS4N(LL)-MACCI4N(LR)

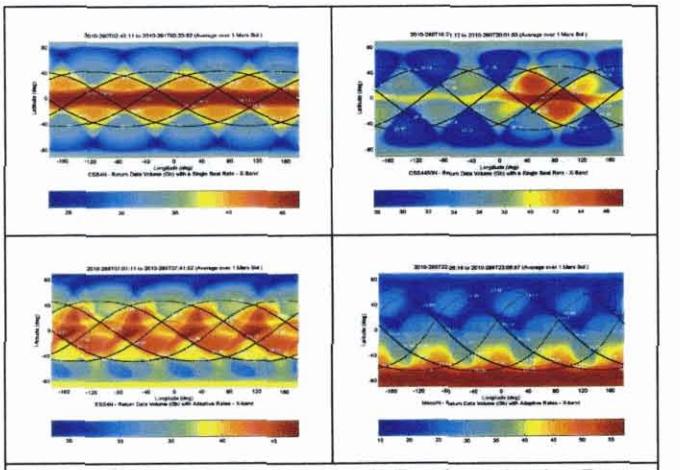

Figure 9. Return Data Volume X-Band – Adaptive Rate CCS4N(UL)-CSS4450N(UR)-ESS4N(LL)-MACCI4N(LR)

5. SUMMARY

In this paper we describe an orbit design aide tool, called Telecom Orbit Analysis and Simulation Tool (TOAST). We emphasize particularly the use of TOAST to the 2009 Mars Telecommunication Orbiter (MTO) although with some modifications TOAST can be used for studying and selecting orbits for any planet such as the Jupiter Icy Moon Orbiter or Lunar Orbiter. Our approach takes into consideration the both the geometry and telecommunication information the orbiter can provide. By specifying the six orbital elements for an orbit, a time frame of interest, a horizon mask angle, and some telecom parameters such as the transmitting power, frequency, antenna gains, antenna losses, link margin, received threshold powers for the rates, etc. this tool enables the user to view the animation of the orbit in two- and three-dimensional different telecom metrics at any point on the Mars, namely the global planetary map. Particular metrics include the (i) number of contacts, (ii) total contact duration, (iii) maximum communication gap, (iv) maximum supportable rate (v) return data volume at a best single rate or with an adaptive rate, along with the (vi) orbiter's footprint, and (vii) the local solar times. Unlike other existing tools, which provide mostly geometry and the view periods for the orbiter and a single location on the planet, our tool incorporates the link analysis to generate the telecom performance metrics for the entire planet. The added capabilities allow the user the extra degree of freedom in deciding the orbit and focusing on meeting specific mission requirements such as what type of supportable data rates can be closed, how much the data throughput are expected, and how long the time gap is between communication periods. The telecom predicts generated by our tool for different candidates lay the foundation that can be use for selecting the final orbit. We

also generate the contact and telecom global maps for four among the forty potential candidates.

ACKNOWLEDGEMENTS

This research was carried out jointly by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United State Government or the Jet Propulsion Laboratory, California Institute of Technology.

REFERENCES

[1] Pedro Ramon Escobal, *Methods of Orbit Determination*, Florida: Krieger, 1976.

[2] Tom Logsdon, *Orbital Mechanics – Theory and Applications*, New York: John Wiley & Sons, 1998.

BIOGRAPHIES

Dr. Charles H. Lee *is an Associate Professor of Mathematics at the California State University Fullerton (CSUF) and a faculty part time staff in the Communications Systems Research Section (331) at the Jet Propulsion Laboratory. Before becoming a faculty member in 1999, he spent three years as a Post-Doctorate fellow at the Center for Research in Scientific Computation, Raleigh, North Carolina, where he was the recipient of the 1997-1999 National Science Foundation Industrial Post-Doctorate Fellowship. His research has been Computational Applied Mathematics with emphases in Control, Fluid Dynamics, Smart Material Structures and recently Telecommunications and Biomedical Engineering. He received his Doctor of Philosophy degree in Applied Mathematics in 1996 from the University of California at Irvine.*

Dr. Kar-Ming Cheung *is a Technical Group Supervisor in the Communications Systems Research Section (331) at JPL. His group provides telecom analysis support for JPL missions, and develops the operational telecom analysis and predict generation tools for current and future JPL missions and the DSN. He received NASA's Exceptional Service Medal for his work on Galileo's onboard image compression scheme. He was the Manager of the Network Signal Processing Work Area of NASA's Deep Space Network (DSN) Technology Program. He has authored or co-authored 6 journal papers and over 20 conference papers in the areas of error-correction coding, data compression, image processing, and telecom system operations. Since 1987 he has been with JPL where he is involved in research, development, production, operation, and management of advanced channel coding, source coding, synchronization, image restoration, and link analysis schemes. He got his B.S.E.E. degree from the University of Michigan, Ann Arbor in 1984, his M.S. degree and Ph.D. degree from California Institute of Technology in 1985 and 1987 respectively.*