Design and Architecture of the Mars Relay Network Planning and Analysis Framework

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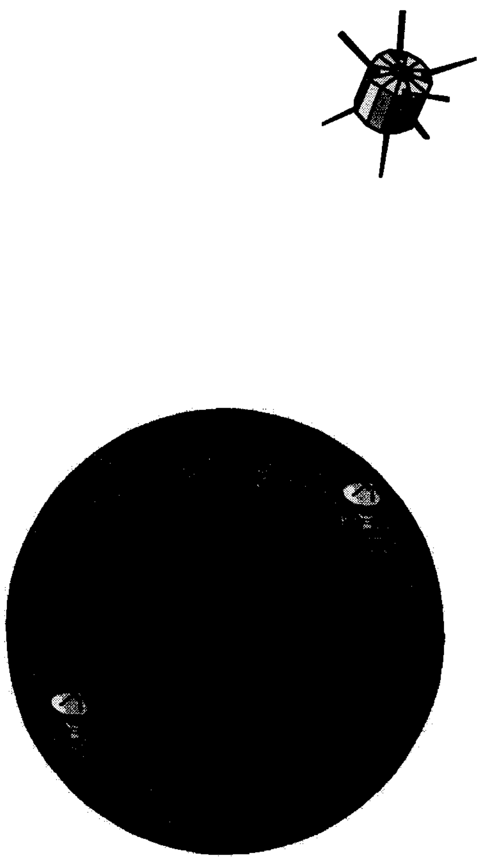
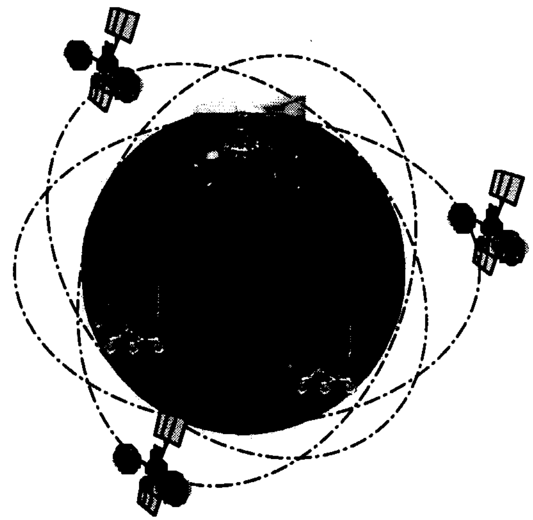
OUTLINE OF PRESENTATION

- Mars Communication Network
- Proposed Design and Architecture
- Mathematical Framework for Communication Network
- Operational Constraints & Requirements
- Simulation and Optimization for a Sample Mars Communication Network
- Summary & Conclusions

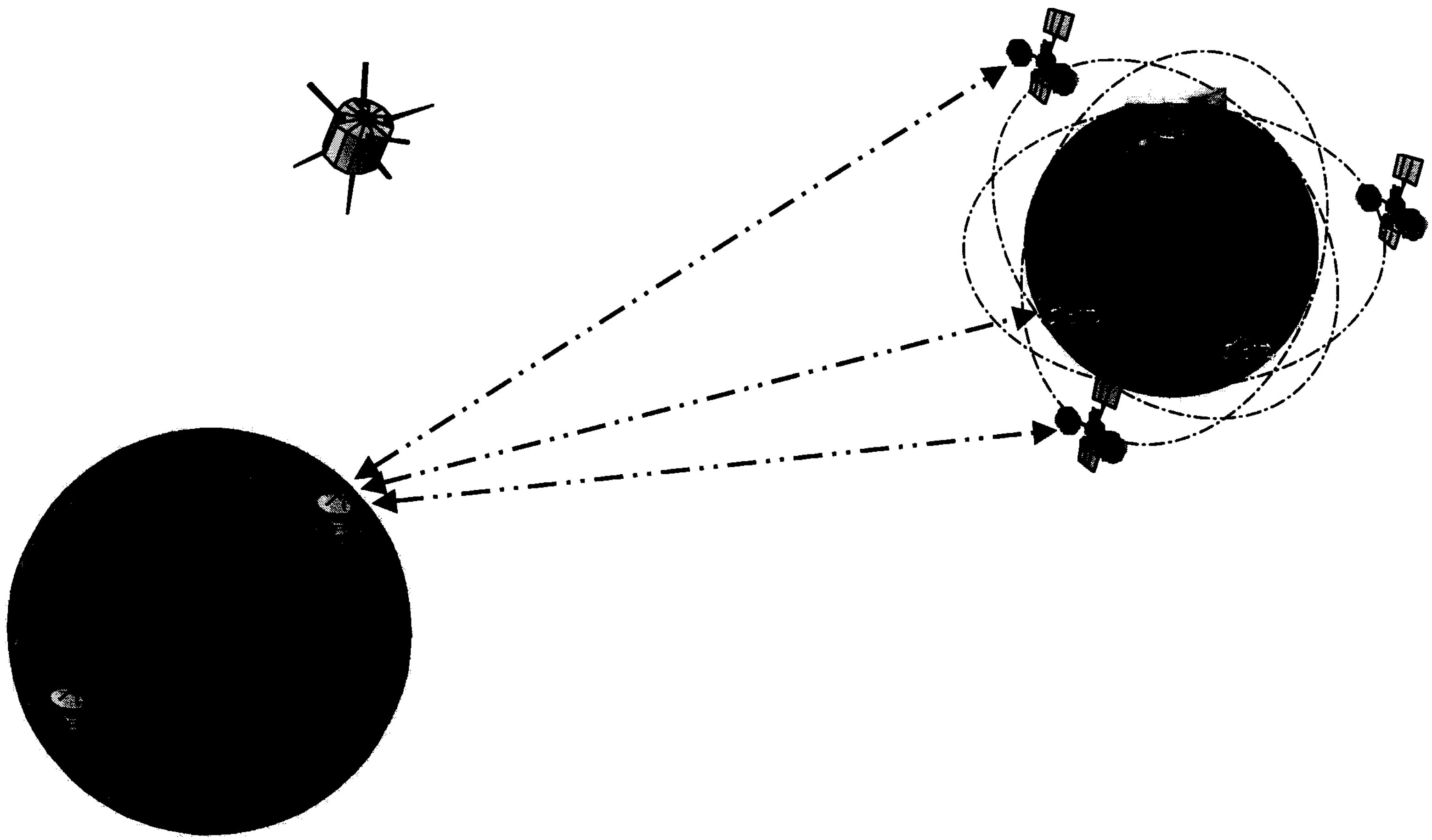
MARS COMMUNICATIONS NETWORK



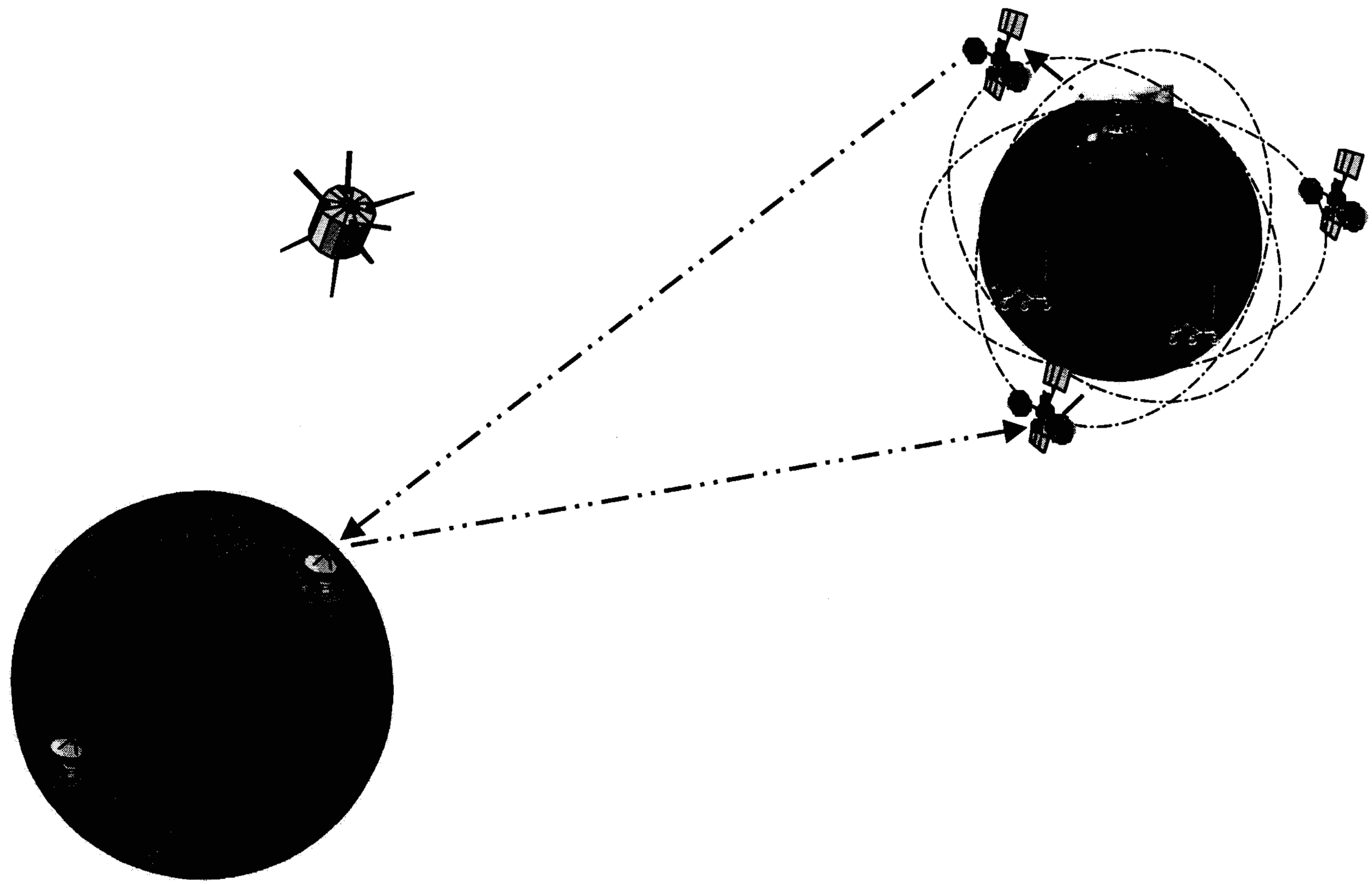


- MGS
- Odyssey
- Mars Exploration Rovers
- British Beagle
- Japanese Nozomi
- Mars Reconnaissance Orbiter
- Future Mars Missions:

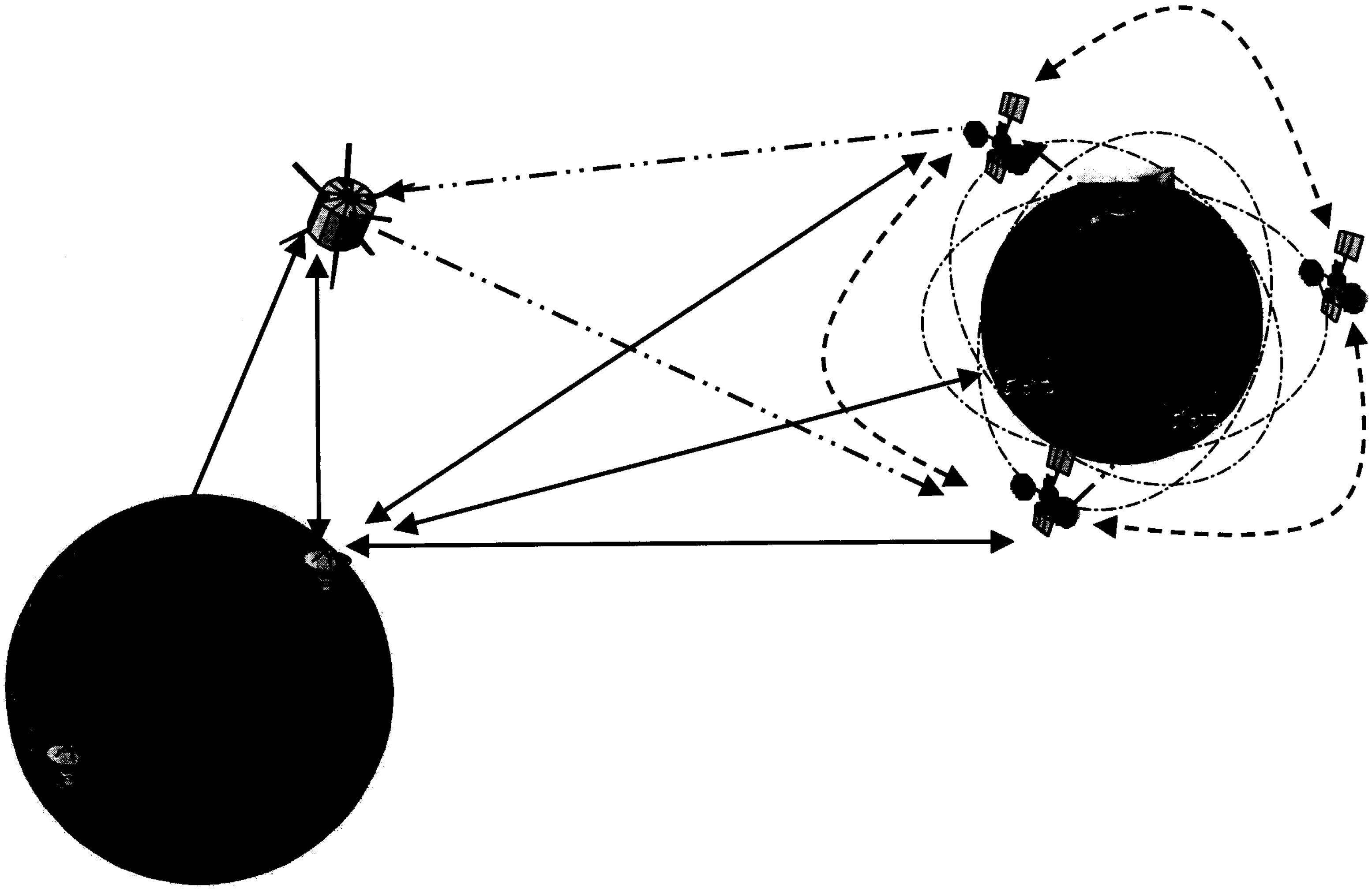
CURRENT MARS COMMUNICATIONS



NEAR-FUTURE RELAY MARS COMMUNICATIONS



FUTURE MARS COMMUNICATIONS NETWORK

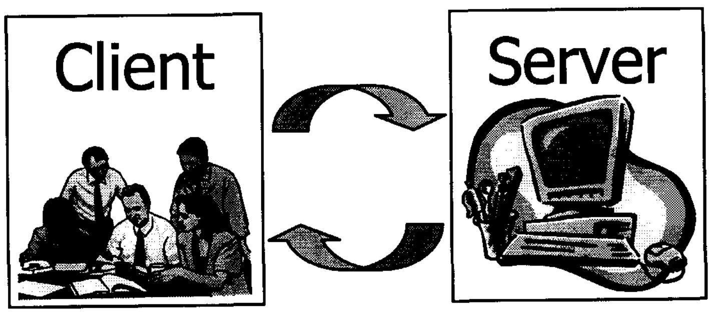


Design Approach for a Relay Network

1. Client-server software architecture
2. Modeling and simulation environment of the end-to-end network link performance and activities
3. Planning and scheduling methodology that optimizes the network resource usage subjected to various constraints of deep space communications.

Client-server Software Architecture

- Thin client/fat server deployment model
- Accessibility is possible through
  - a local network socket in a batch mode
  - a graphical user interface with a www session
  - a personal computer



The client submits parameters along with rules and instruction to the server.

- Modeling, Simulation, Optimization End-to-end Network
- Back-ended by up-to-date database of trajectory profiles, communication assets and performances, hardware, etc.
- De-coupled features of visualization, computation, and database functions to allow plug-and-play of various functions and extensions.
- Returns requests to the client.

Modeling & Simulating End-to-end Network

- Link Resource
  - Link analysis (gain, loss, ant. pattern, weather, etc.)
  - Point-to-point supportable data rate (time-dependent)
- Spacecraft Dynamic Events (range & pointing)
  - Quiescent (stable and predictable link performance)
    - Cruising or Mapping
  - Dynamics (direct impacts on the link performance)
    - Launch, Safing, Orbital Insertion.
    - Trajectory Correction, Spinning, Coning, Roving & Tilting
- Operation Constraints
  - Geometry, hardware, mission requirements, priority, flight rules, calibration, requisition, maintenance, human policy.

Network Optimal Planning & Scheduling

- Constrained optimization problem
  - Objectives
    - minimize the communicating time
    - Minimize delaying time
    - maximizing data throughput
  - Constraints
    - Geometry
    - Operational
    - Communication
- Available Software
  - ILOG, MATLAB Opt. Toolbox, Mathematica Optimizer
  - JPL's (APGEN, ASPEN, TIGRES).

ADVANTAGES

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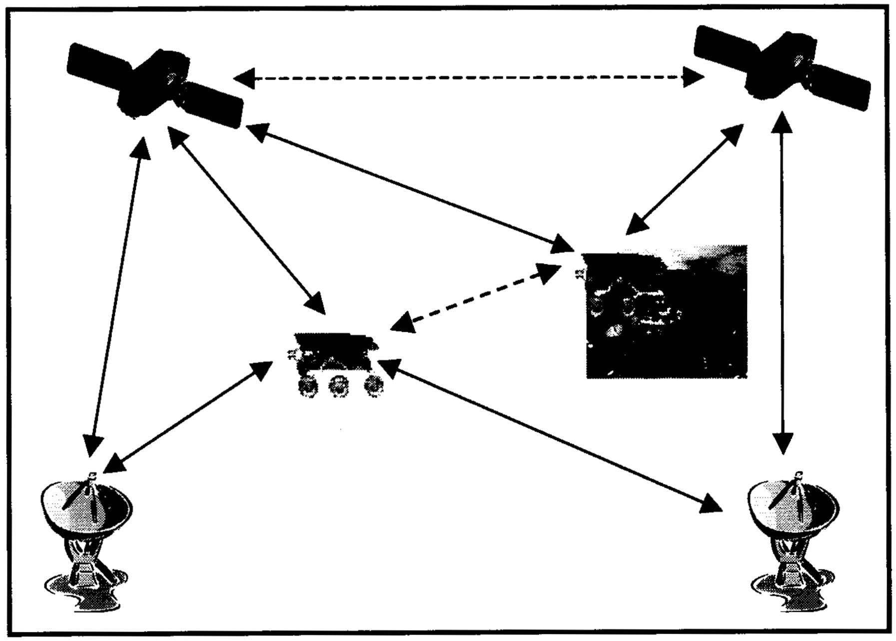
- Up-to-date & Centralized Data
- Easy & Secured Accessibility
- Quicker Turn-Around Time
- Complete Network Modeling & Simulating
- Shorter Communicating Time
- Better Network Link Configuration
- Lower Mission's Operation Costs
- More Missions Supported
- Alleviate Possible DSN Congestion

MATHEMATICAL FRAMEWORK



Communication Network:

- L Surface Elements $\{SE_1, SE_2, \ldots, SE_L\}$
- N Orbiters $\{Orb_1, Orb_2, \ldots, Orb_N\}$
- M DSN Stations $\{GS_1, GS_2, \ldots, GS_M\}$

MATHEMATICAL FRAMEWORK

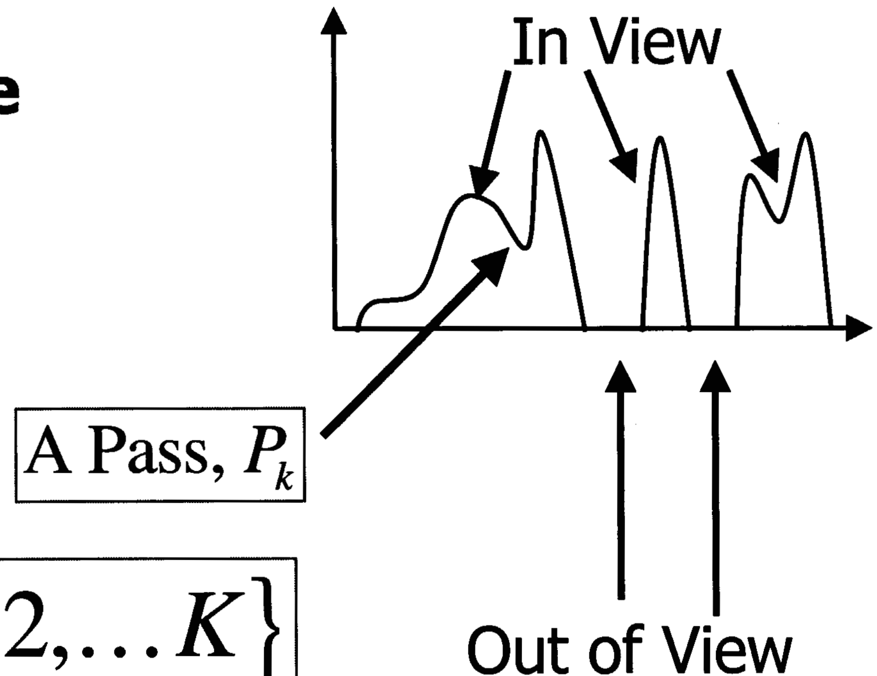
- Downlink Planning ~ Uplink Planning
  - Downlink only in this paper to demonstrate feasibility.
- Surface Element to Earth
  - Directly or relayed via an orbiter
- Orbiter to Earth
  - Directly
- Orbiter-to-Orbiter & SE-to-SE are not considered
  - One-hop Relay

MATHEMATICAL FRAMEWORK

- Trajectory(NAIF or High-order Orbital Mechanics Tool)
  - Range, Elevation Angle,Terrain, Mask Angle, Occultation,etc.
- Telecom Requirements
  - Antenna Pattern, Frequency Bands, Weather Forecast, etc.

Supportable Data Rate

$$S_{XMT,RCV}(t)$$



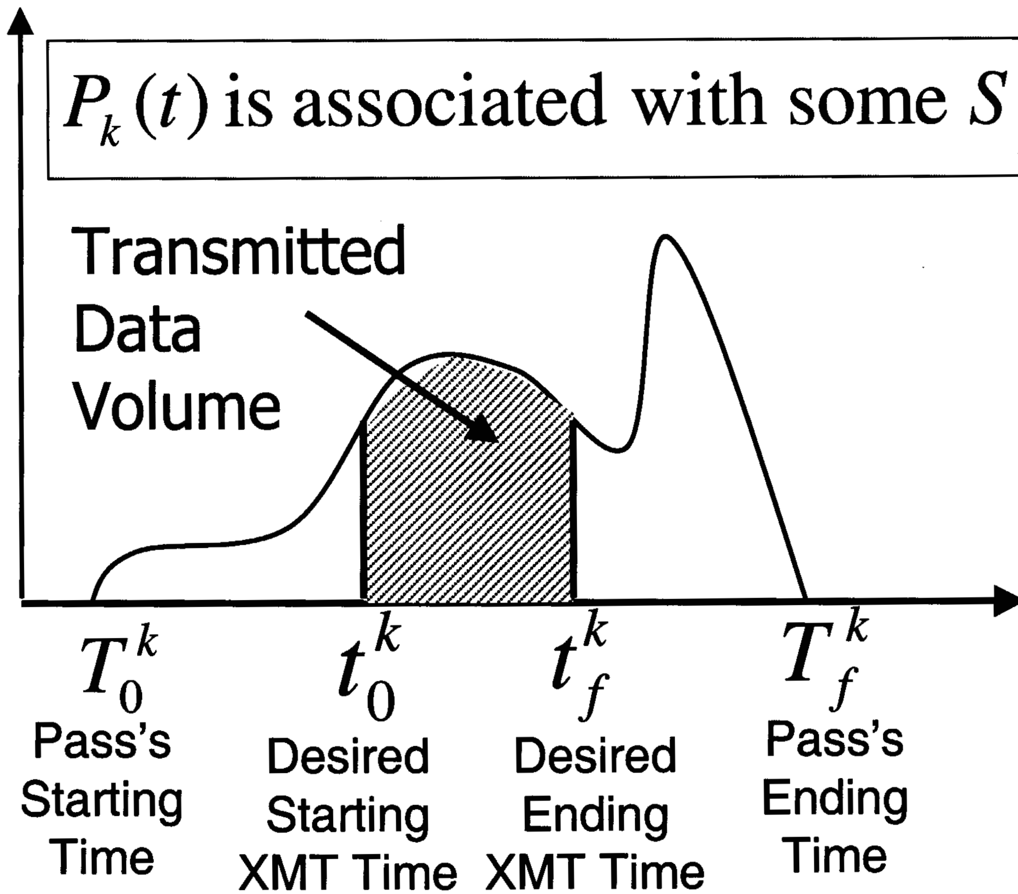
K Possible Passes

$$\{P_k \mid k = 1, 2, \ldots K\}$$

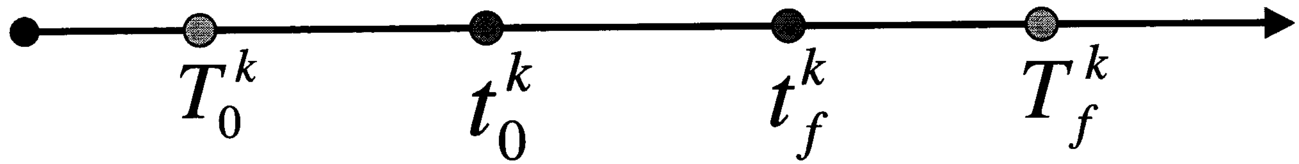
MATHEMATICAL FRAMEWORK

Each Pass $\{P_k(t)\}_{k=1}^{K}$ Represents the Communication between a Transmitter and a Receiver within the Network.

$P_k(t)$ is associated with some $S_{XMT,RCV}(t)$

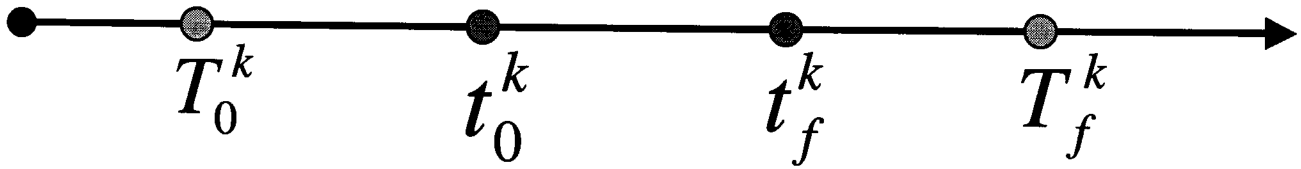


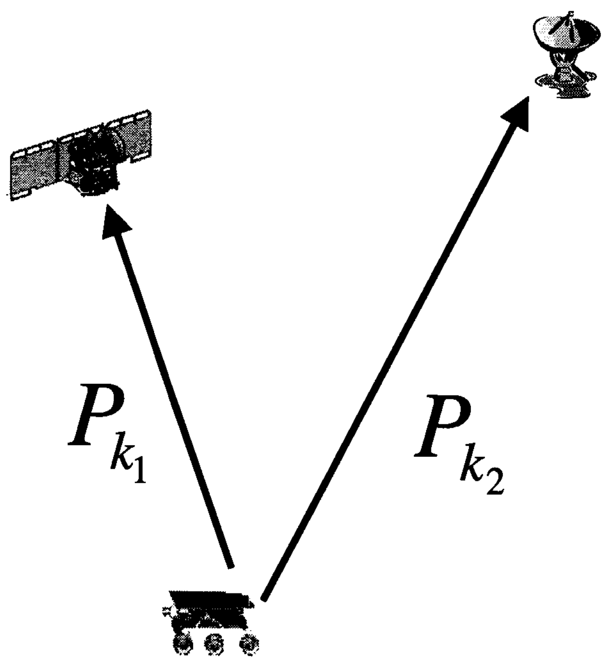
OPERATIONAL TIME CONSTRAINTS



- A Pass Has to Be Long Enough $$T_f^k - T_0^k \geq T_{pass}$$
- Acquisition/Calibration Before XMT $$t_0^k \geq T_0^k + \tau_k$$
- Start Time Smaller Than End Time $$t_f^k \geq t_0^k$$
- XMT Time Stays Within the Pass $$T_f^k \geq t_f^k$$

OPERATIONAL TIME CONSTRAINTS





$$[t_0^{k_1}, t_f^{k_1}] \bigcap [t_0^{k_2}, t_f^{k_2}] = 0$$

DATA VOLUME REQUIREMENTS

DATA VOLUME THROUGHPUTS FROM PASS P_k

$$DV_k = \int_{t_0^k}^{t_f^k} S_{XMT,\,RCV}^{K}(t)\,dt$$

TOTAL DATA VOLUME THROUGHPUTS FROM A SPACECRAFT MUST EXCEED ITS REQUIREMENT

$$\sum_{k=1}^{K} DV_k \geq RDV_i.$$

P_k *involves* SC_i

STORAGE CAPACITY CONSTRAINTS

$$\int_{t_0^k}^{t_f^k} S^{K}_{SE_l,\,Orb_n}(t)\,dt + E_{Orb_n}(t) \le C_{Orb_n}$$

E_{Orb_n} (t) Existing data currently being stored onboard

C_{Orb_n} Orbiter's Storage Capacity Onboard

DATA VOLUME OBJECTIVE FUNCTION

To achieve link efficiency we require the communicating time to be optimal, so that the total data throughput from the network is maximal.

$$C_{DV}(t_o^1, t_f^1, \ldots, t_o^K, t_f^K) = -\sum_{k=1}^{K} DV_k$$

XMT TIME OBJECTIVE FUNCTION

To achieve link efficiency we require the communicating time to be as small as possible, so that more missions can be supported with the same resources.

$$\min \sum_{k=1}^{K} (t_f^k - t_0^k)$$

CONSTRAINED OPTIMIZATION

MINIMIZE

$$C(X) = \omega\, C_{DV}(X) + (1-\omega)\, C_{TIME}(X)$$

$$X = \begin{bmatrix} t_o^1 \\ t_f^1 \\ \vdots \\ t_o^K \\ t_f^K \end{bmatrix}$$

$$C_{DV}(t_o^1, t_f^1, \ldots, t_o^K, t_f^K) = -\sum_{k=1}^{K} DV_k$$

$$C_{TIME}(t_o^1, t_f^1, \ldots, t_o^K, t_f^K) = \sum_{k=1}^{K} (t_f^k - t_0^k)$$

$$\omega \in [0, 1]$$

SUBJECT TO ...

CONSTRAINED OPTIMIZATION

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SUBJECT TO

$$AX \le B$$

$$L_B \le X \le U_B$$

$$[F(X); G(X); H(X)]^T \le 0$$

$$A = \begin{bmatrix} 1 & -1 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & \vdots & \vdots \\ \vdots & \vdots & & & \ddots & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 1 & -1 \end{bmatrix}_{K \times 2K}$$

$$B_k = 0 \quad k = 1,2,\ldots K$$

$$F_j(X) = \begin{cases} (t_f^{k_1} - t_0^{k_2})\,\mathrm{sign}(t_f^{k_1} - t_0^{k_1}) & T_{k_1}^* < T_{k_2}^* \\ (t_f^{k_2} - t_0^{k_1})\,\mathrm{sign}(t_f^{k_2} - t_0^{k_2}) & \text{otherwise} \end{cases}$$

$$G_i(x) = \sum_{\substack{k=1 \\ P_k \text{ involves } SC_i}}^{K} DV_k - RDV_i \quad i = 1, \ldots, L+N.$$

$$L_B = \begin{bmatrix} T_o^1 \\ T_o^1 \\ \vdots \\ T_o^K \\ T_o^K \end{bmatrix} \qquad U_B = \begin{bmatrix} T_f^1 \\ T_f^1 \\ \vdots \\ T_f^K \\ T_f^K \end{bmatrix}$$

$$H_n(X) = \int_{t_0^k}^{t_f^k} S^K_{Lander_l,\, Orbiter_n}(t)\,dt + E_{Orbiter_n} - C_{Orbiter_n}$$

A SAMPLE MARS NETWORK

Lander	Longitude	Latitude	Altitude	Mask Angle
1	175	-15	0	15
[illegible]	283	[illegible]	0	15
3	354	-2	0	15
4	82	-43	0	15

Semi-major axis	Eccentricity	Inclin. Angle	Asc. Node	Arg. of Perigee	Time at Perigee
4084 km	0.010814	20	249	153	0
3772 km	0.011474	51	87	344	0
4052 km	0.009869	-89	292	317	0
4008 km	0.012156	53	336	251	0
3890 km	0.056136	26	46	110	0

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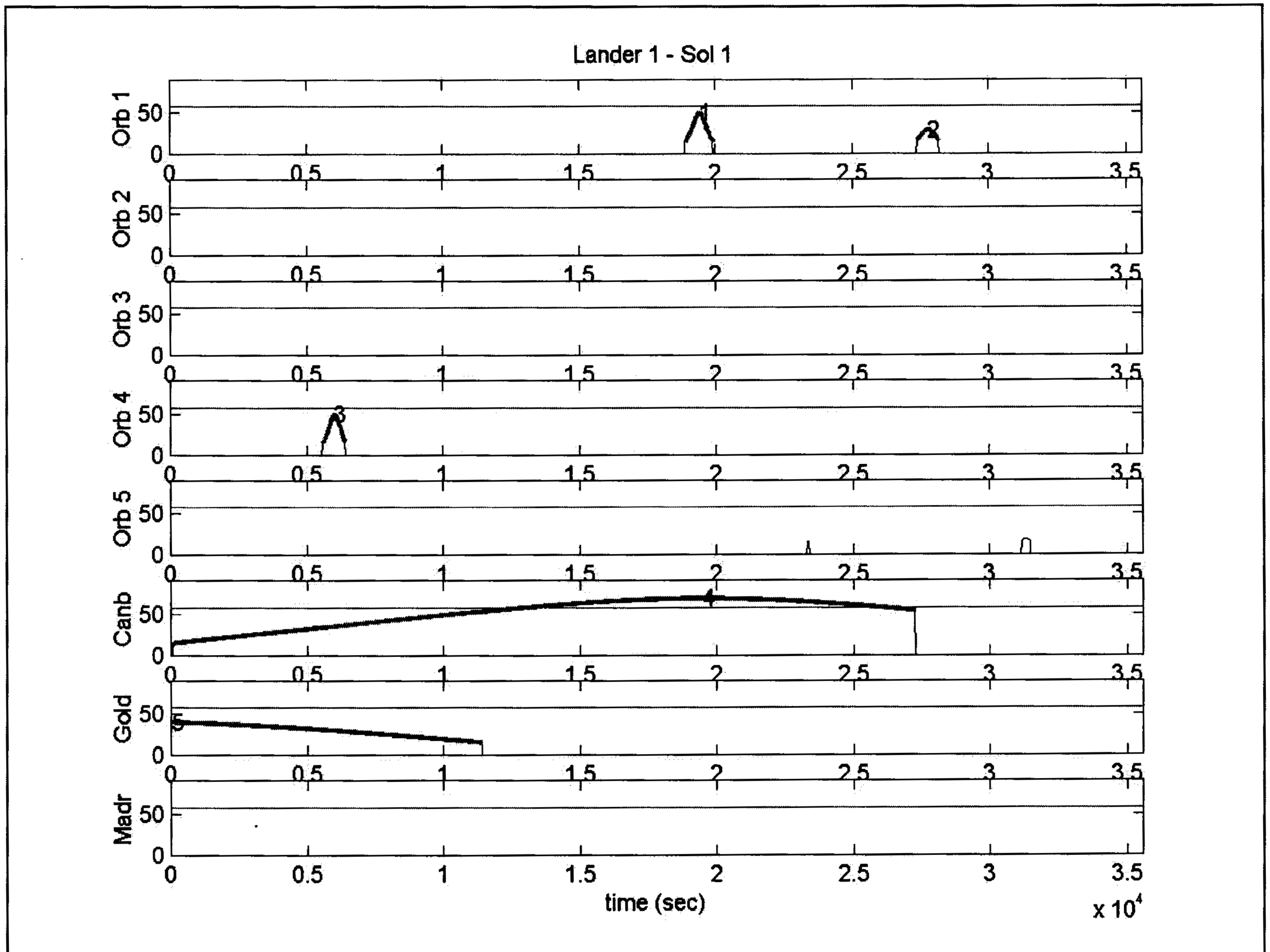

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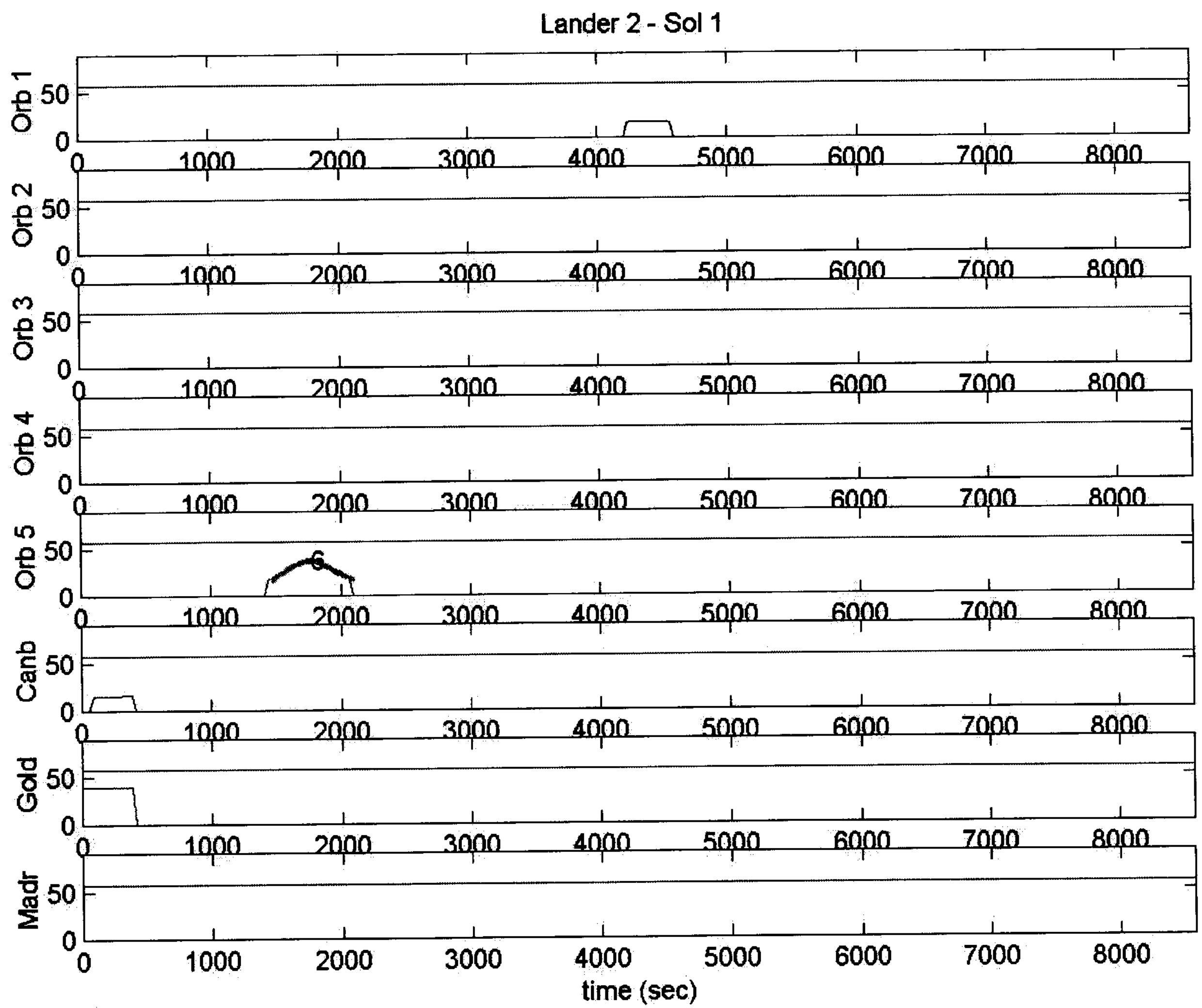

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A SAMPLE MARS NETWORK

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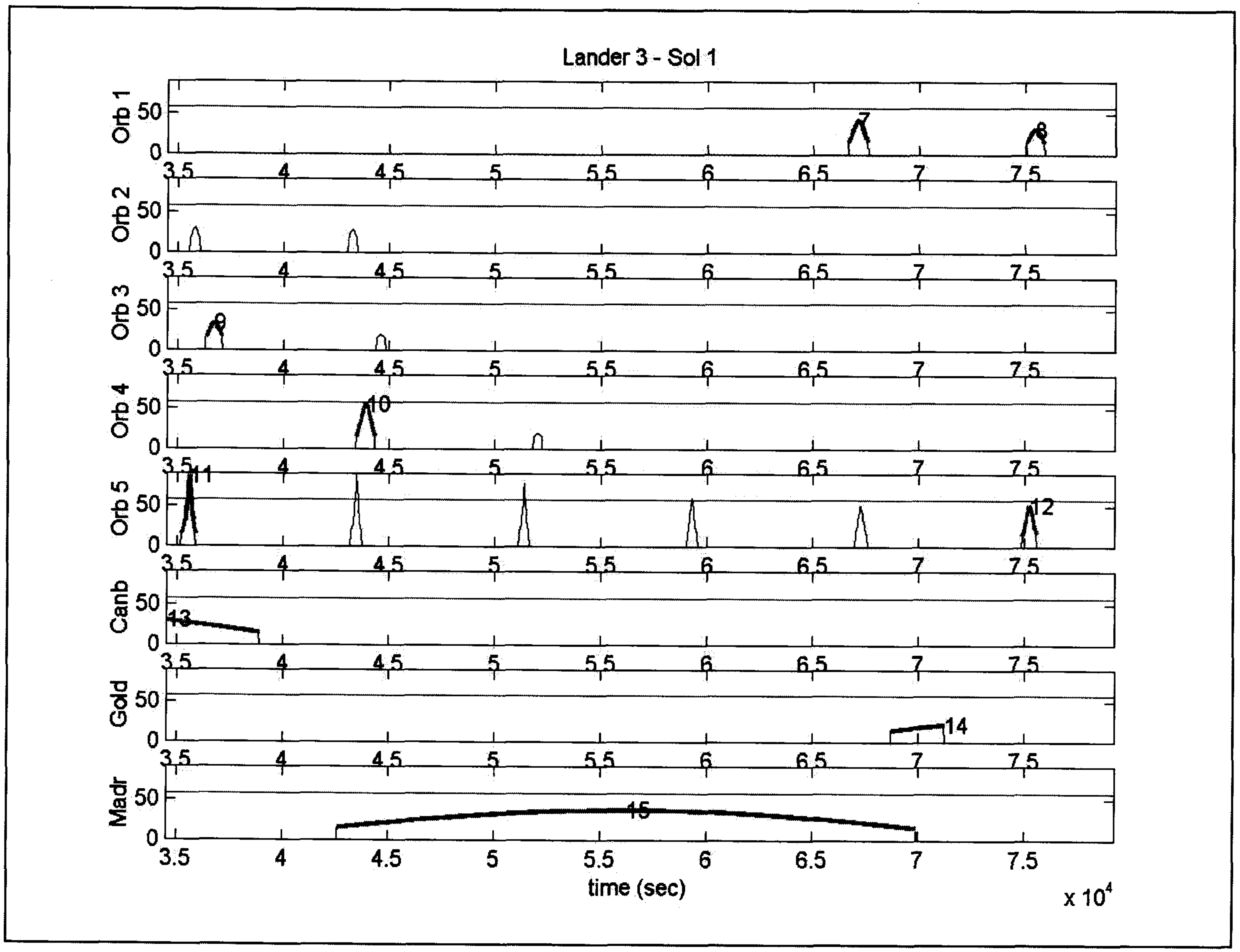

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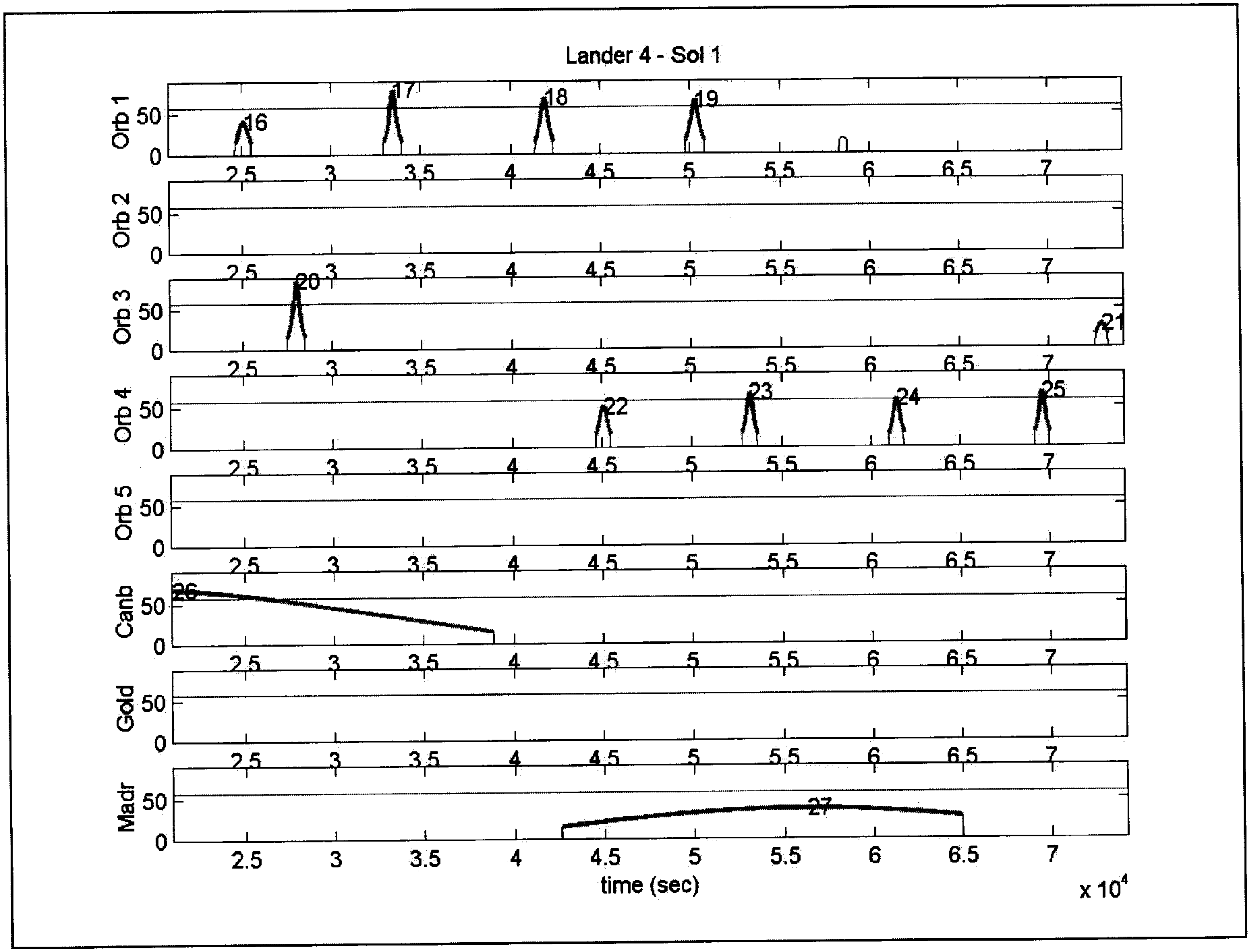

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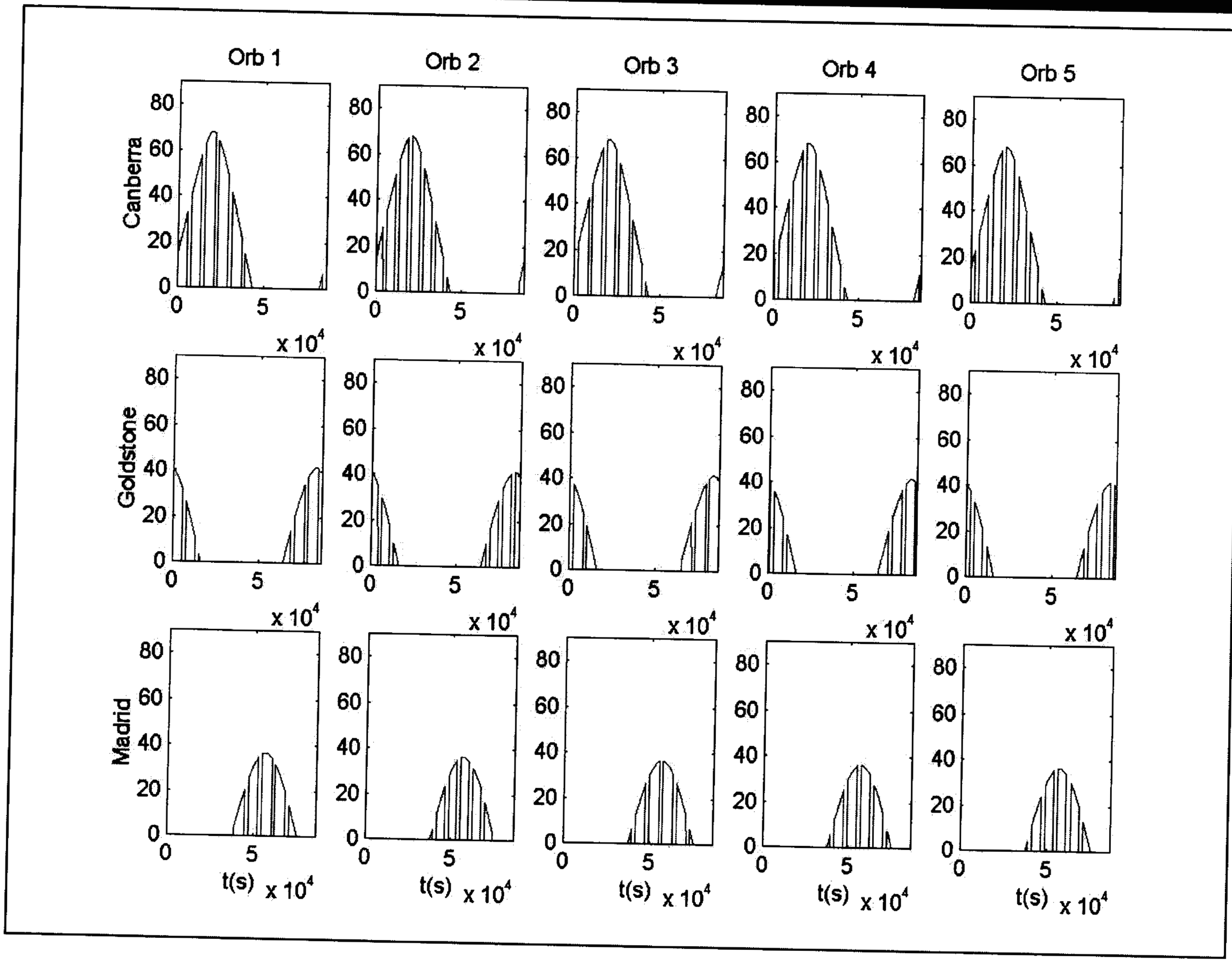

SIMULATION RESULTS

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1	18930	18931	18931	19920
2	27420	27420	28170	28170
3	5610	5610	5610	6420
4	120	5610	27270	27270
5	30	30	5610	11430
6	1470	1470	2100	2100
7	66660	66660	67560	67560
[redacted]				
9	36330	36330	37080	37080
10	43470	43470	44219	44340
11	35190	35190	35850	35850
12	74910	74910	75502	75570
13	34530	34530	35190	38880
14	68730	68730	71220	71220
15	42630	44219	66660	69900
16	24690	25530	25530	25530
17	32970	32970	33960	33960
18	41400	41400	42390	42390
19	49800	49800	50790	50790
20	27510	27510	28470	28470
21	72630	72630	73290	73290
22	44700	44700	45480	45480
23	52830	52830	53572	53640
24	61020	61020	61830	61830
25	69210	69210	69990	69990
26	20970	20970	25530	38880
27	42630	53572	61020	64950

CONCLUSIONS

- Design and Architecture for Mars Relay Network
- Develop Mathematical Framework for Communication Network
- Construct Operational Constraints & Requirements
- Transform & Cast Problem into Multi-criteria and Multi-objective Constrained Optimization Problem
- Simulation and Optimization for a Sample Mars Communication Network
- Our Result Indicates Significant Promises as the Optimal Schedule Satisfies the Operational Constraints While Achieving the Communication Efficiency.