Spacecraft Demand Access:
Autonomy for Low-Cost Planetary Operations

Donald Sweetnam
Henry Hotz

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Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 911090
818-354-7771 (v), 818-354-9068 (f)
dsweetnam@jpl.nasa.gov

Introduction

In this paper we describe a new concept and prototype for dramatically reducing the cost of contact with planetary spacecraft. Known as Spacecraft Demand Access, a suite of spacecraft and ground automation technologies, it enables future intelligent spacecraft to act as initiators of cost effective contact with the ground - doing it only when necessary. It represents a reversal of the traditional, labor intensive and costly ground initiated procedures for contact. It is our objective that implementation of Spacecraft Demand Access technologies to support future missions reduces the cost of contact with planetary spacecraft by a factor of 10, while increasing the volume of information from a single contact by at least a factor of 2.

Background

The traditional approach that NASA has used for contact with planetary spacecraft is built around a labor intensive process of developing complex time-based sequences, simulating their detailed behavior, uplinking commands to the spacecraft, monitoring their actual behavior with lots of downlinked telemetry, and then analyzing in even more detail the performance of the sequence. In effect, it is intended that nothing happen onboard that has not been part of a meticulous pre-tested plan, and that everything that does happen is analyzed at length in real-time or after the fact.

In addition, a second non-technical process has been at work to maintain the cost-of-contact at high levels. This has been the notion that (at least from the mission perspective) spacecraft tracking is 'free'. By isolating the cost associated with operating a planetary mission from the cost of tracking that mission in different organizations, NASA has encouraged missions to make tradeoffs that reduce their own direct costs by increasing the amount of tracking.

We believe that execution of these processes has resulted in requirements by planetary missions tor very high levels of contact with their spacecraft. Figure 1 shows an analysis of the amount of contact with planetary spacecraft between 1990 and 1996. It indicates that most spacecraft are in contact with the ground between 1 and 2 passes per day (a pass is defined here to be 8 hours), with some missions consuming support continuously and/or with multiple arrayed antennas.

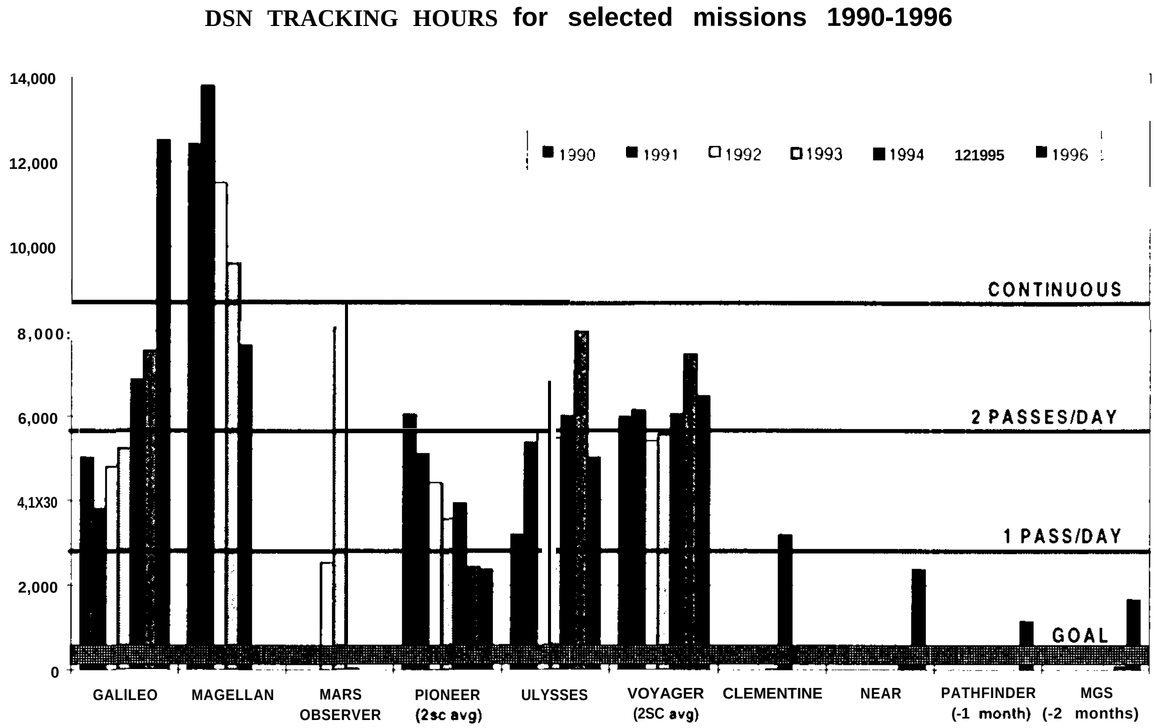

Figure 1 DSN Tracking Hours for selected missions 1990-1996

At a cost to NASA of $ 1-3K per hour for antenna time (not including real-time ops support team costs), it is easy to see that the cost of contact can easily exceed $ 10M per spacecraft per year. In the current NASA environment which desires to increase the mission rate while at the same time instituting full cost accounting for total mission costs, these kinds of expenses have been deemed unacceptable.

In order to begin to understand how to resolve this 'contact conundrum', it is necessary to look at the underlying technical reasons why contact is necessary. We have found that mission requirements for contact with planetary spacecraft can be decomposed into four parts, a) health and safety, b) science telemetry, c) radiometric navigation, and d) commanding. Current methods for contact with spacecraft often utilize 2 or more of these components simultaneously (e.g., commanding, radiometric navigation, and telemetry are often done on the same 2-way coherent link) . We make the point that any efforts to effectively reduce the cost of contact must make provision for each of these components; just solving one component may not reduce the amount of contact at all or could even cause it to increase!

Concept

In order to achieve our objective, we have devised a concept that utilizes a suite of five technology components,

1. Onboard navigation
2. Onboard self-monitoring
3. Beacon Signaling
4. High Efficiency Tracking
5. Virtual Emergency Room

Figure 2 shows these technology components and their interrelationships. Our operations concept is as follows: The spacecraft, utilizing an intelligent on board system (such as is planned for New Millennium DS I), monitors its own subsystems and manipulates resources, generating commands as necessary. The spacecraft also establishes its own position, velocity, and orientation utilizing an onboard attitude control system and navigation (such as optical nav). The spacecraft then transmits a simple Beacon signal to the ground that indicates "I'm OK", or "I need HELP!", or "I want to dump data".

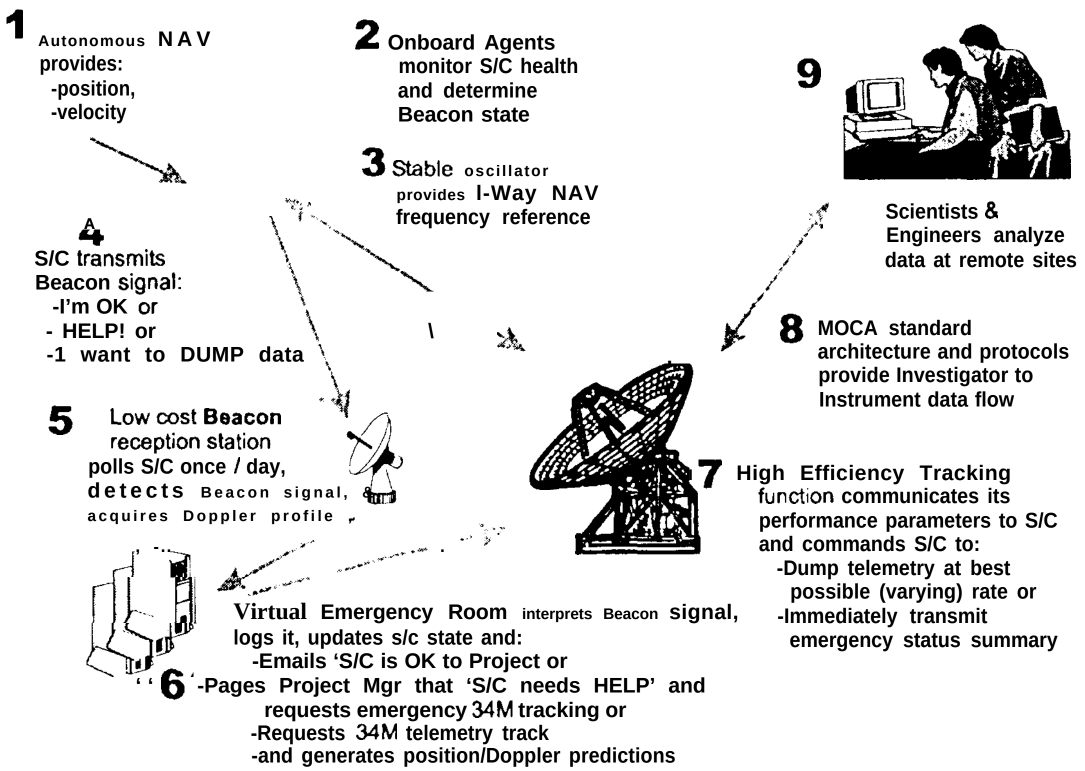

Figure 2 Spacecraft Demand Access concept

This Beacon signal is received on the ground by a low cost (3-6 meter) antenna that polls each spacecraft once per day for its beacon state. This information is forwarded to a Virtual Emergency Room (no operators required) which interprets the Beacon signal, logs it and decides what action is necessary.

In the simplest case, an e-mail message is forwarded to the mission manager that says "Your spacecraft is OK today". In the emergency case, the mission manager can be immediately "beeped" to respond, while at the same time a request for an emergency pass from a large (34-70 meter) antenna is forwarded to the network scheduling system. In the usual case, the Virtual Emergency Room, using a mission specified urgency algorithm, forwards a request for a telemetry pass with a large (34-70 meter) antenna to the network scheduling system.

The large antenna, utilizing the High Efficiency Tracking technology, communicates its performance parameters for the next 8-12 hours (including weather) to the spacecraft in near-real time, and commands the spacecraft to send telemetry at its best possible (varying) rate within the envelope based on those parameters and the spacecraft's own telecom state. This information, primarily science telemetry, is forwarded to science investigators.

This remainder of this paper will concentrate on the prototyping efforts at JPL for the Beacon Signaling, High Efficiency Tracking, and Virtual Emergency Room.

Implementation

The Beacon Signaling system is implemented onboard the spacecraft as follows. An intelligent onboard software module performs a continuous self-monitor activity, utilizing subsystem sensor inputs to establish the spacecraft state and to detect faults. Another onboard module may be able to analyze faults and take corrective action. A beacon mode software module filters the outputs of the self-monitor and correction modules to one of 4 modes. It then accesses the transponder, selects a modulation index of about 90 degrees, and a subcarrier frequency that corresponds to one of the 4 modes, and radiates a downlink similar to that shown in figure 3. In this figure, the simulation is for a spacecraft radiating an "OK" signal, with a Df1 of 125 Hertz. Df2,3,4 could be defined to be 250, 375, 500, or some other arrangement consistent with the particularities of the transponder, receiving equipment and frequency uncertainties (JPL's Small Deep Space Transponder expects to generate Df's between 500 and 5,000 Hertz). Table 4 shows one possible arrangement for implementation of beacon signaling. The choices for frequency separation between modes should be driven by equipment factors; the interpretation of mode meaning and the consequent action taken should be specified by individual projects.

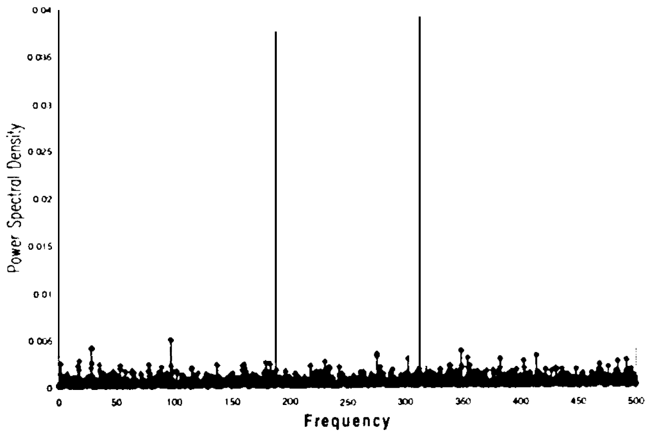

Figure 3 Beacon Signaling simulated spectrum

RF	Beacon Detection System*	Project Specified VER Interpretation (one possibility)	Project Specified VER Action (one possibility)
Carrier Only	-1	S/C not in Beacon Mode	• Report to Project
Telemetry Transmission	-1	S/C not in Beacon Mode	. Report to Project
oft	1	OK	. Report to Project
ot2	2	Probability>30%, HELP? Probability>60%, HELP!	. Immediately Repeat Beacon Detection . Notify Project (beeper) • Request Emergency Pass with 34 meter antenna
o f 3	3	Need to D/L telemetry	. Gel 100 Mbits within a week
Df4	4	Found something interesting	. Get 100 Mbits within a day
No Signal	0	1 day--OK 2 days--OK 3 days - HELP	. Report to Project . Report to Project Same as Df2

* The Beacon Detection System will forward a detection probability rather than a simple message determination. This will allow the VER to adjust Its actions based on project-specific knowledge of the criticality of the message A 30% possibility of a message 2 (help) may trigger an "emergency' repeal beacon pass with no special project notification, while a 60% message 2 might immediately trigger the full emergency pass with notification of project personnel

Table 4 Beacon Signaling mode definition

Figure 5 is a functional description of the Demand Access ground system. There arc 3 primary functional elements, the Beacon Monitor system, the High Efficiency Tracking system, anti the Virtual Emergency Room. An initial implementation could put a beacon monitor antenna at the DSN complexes at Goldstone ancl at Canberra. An initial implementation of the HEF could be to utilize an existing 34 meter antenna at Goldstone. The VER would reside at JPL. Note that the functional allocation is to put the RF and signal processing equipment at the remote sites. while keeping the primary configuration database and interpretation modules local.

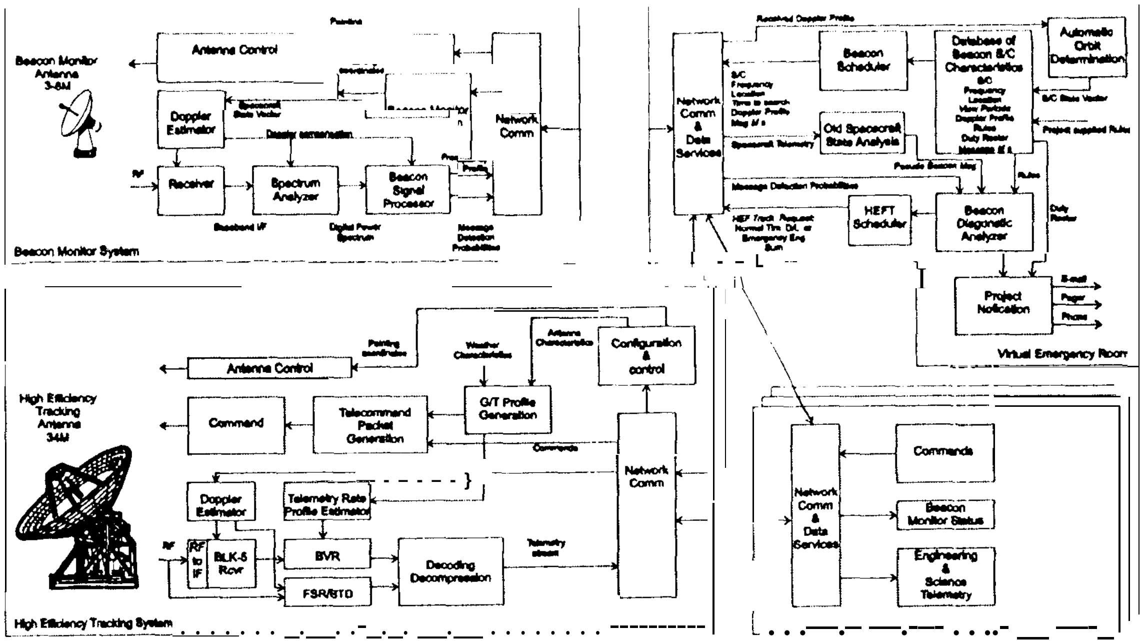

Figure 5 Functional Description of Demand Access ground system

The Virtual Emergency Room (see Figure 5) has the responsibility of controlling the operation of the demand access system. This is a small collection of nominally unattended servers; with humans necessary only for routine maintenance and configuration changes. It contains a database of necessary information, organized by specific mission. A scheduler determines when the beacon reception antennas need to look at which spacecraft. A diagnostic analyzer does the actual interpretation of the detection probabilities received from the beacon antennas, based on the mission supplied rules. A module has been included that can synthesize a beacon mode for old spacecraft.

Note that the beacon signaling system has also been designed to acquire and process 1-way radiometric data, and that the VER has a module for orbit determination. Our preliminary analysis indicates that 1 hour long daily batches of radiometric data is suitable for a moderate precision trajectory prediction capability, good enough to supply antenna pointing and frequency tuning predictions for the beacon system and for the high efficiency tracking system. This has enormous benefit, since the system can maintain its own prediction database without expensive external mission interfaces, and more to the point, it doesn't cause missions to have to do more radiometric tracking with costly large antennas.

The High Efficiency Tracking block diagram is shown in Figure 5. The spacecraft-ground 'handshake' process for executing a HEF track is shown in Figure 6. The upper boxes in Figure 6 represent onboard functions. The dashed lines represent spacecraft-ground communication. We have built a simulation model to characterize the process; each major event and its example time of execution is shown under each box.

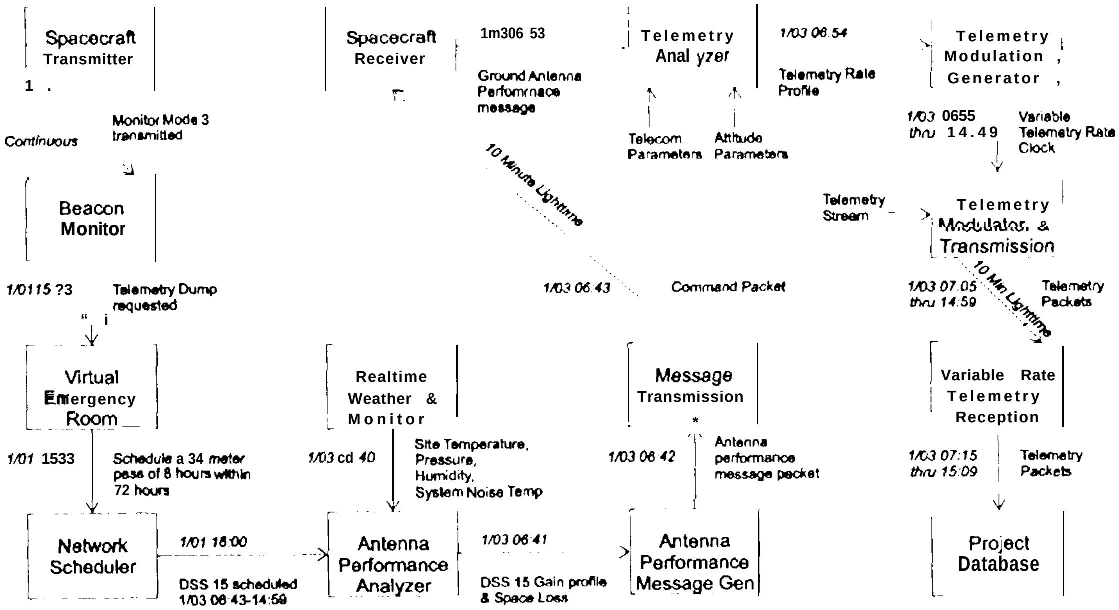

Figure 6 High Efficiency Tracking process

The basic concept behind High Efficiency Tracking is to enable the spacecraft to send telemetry to the ground at a near optimal and variable rate, based on near-real time conditions at the ground station and onboard the spacecraft. On the ground this means assembling a ground antenna performance envelope immediately prior to the start of contact that includes the latest information on gain and weather conditions. On the spacecraft this means developing a downlink transmission rate profile (based on antenna selection, rf amplifier power, and pointing losses) and then transmitting the data according to the profile. Figure 7 shows how an example HEF pass performance envelope and downlink rate might look, and compares them with current methods for establishing tracking rates. In this particular case, High Efficiency Tracking would provide a factor of 2.5 increase in returned data over an 8 hour pass.

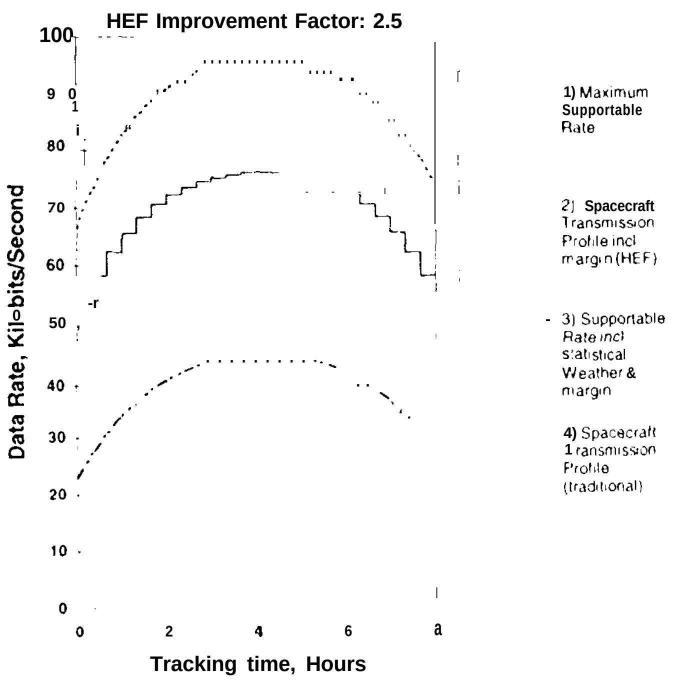

Figure 7 High Efficiency Tracking performance

We have developed a simulation model to determine the utility of demand access for downlinking telemetry under conditions common in planetary missions. The objective is first to find a viable process (see Figure 8), and then to determine how flexible or resilient that process is to varying loads. We have defined the flexibility metric to be the amount of time that the ground can wait to respond with a HEF antenna after one has been requested by the beacon signal (shown on the figure as the "Flexible Schedule Interval"). We have then shown. in Figure 9, the result of the model for -i mission types Here the same flexibility metric is shown as

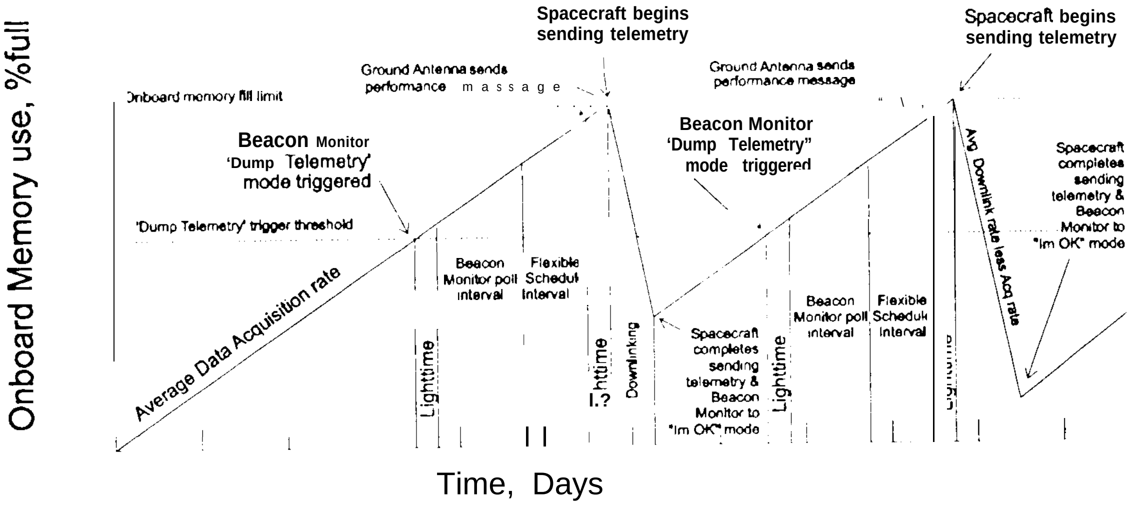

Figure 8 Spacecraft Demand Access process model for telemetry

the "Maximum No-Track Interval", and the amount of flexibility, in days, is enumerated in each bar on the chart. It shows that most missions have at least a week of flexibility in scheduling a track; they would glean significant benefit from HEF. It also shows that the observing phase of a complex data driven mission (such as an older Mars orbiter, without a lot of memory or SNR) probably does not have enough flexibility to benefit from HEF.

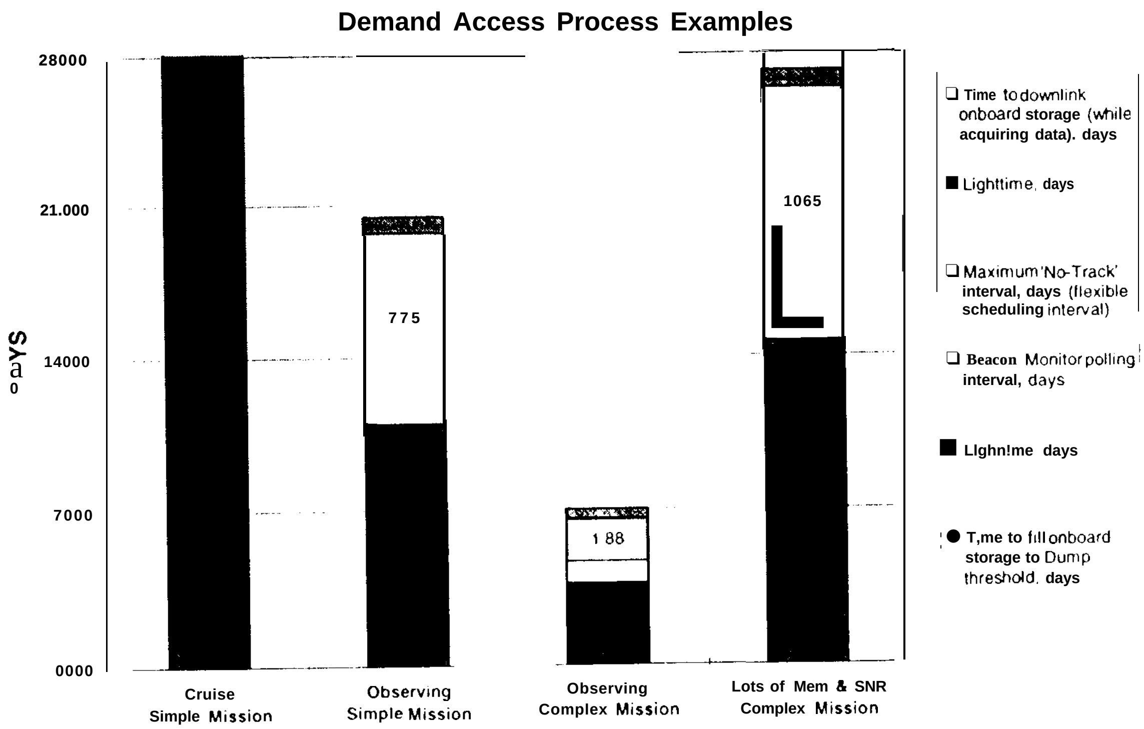

Figure 9 Demand Access Process for common planetary mission types

Conclusion

We believe that implementation of the Spacecraft Demand Access concept will have an enormous impact in lowering the cost-of-contact with planetary missions. We have done a simple calculation (based on actual tracking during the Mars Observer mission cruise phase) showing that substitution of the beacon signaling system for much of the nominal tracking would have reduced aggregate tracking costs from about $10 Million to about $1.4 Million. We have shown above that use of HEF can result in more than a factor of two increase in returned data volume per pass. This gives mission designers the flexibility to 'take a lot more pictures' or cut their tracking cost budget in half.

Currently, at JPL, we have largely completed the development of the Spacecraft Demand Access concept and the bulk of the trade studies. We have developed the detailed design for the Virtual Emergency Room and have begun implementation of the necessary software modules. We are also finalizing test plans to utilize JPL's Flight System Testbed and Simulation Mission Operations Control Center Testbed to run end-to-end tests of the beacon signaling process, high efficiency tracking process and virtual emergency room.

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