# MEXAR / RAXEM communication planning systems

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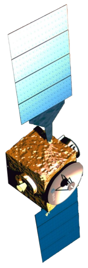
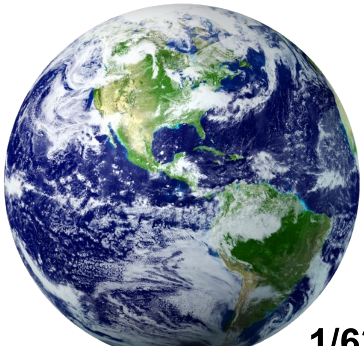
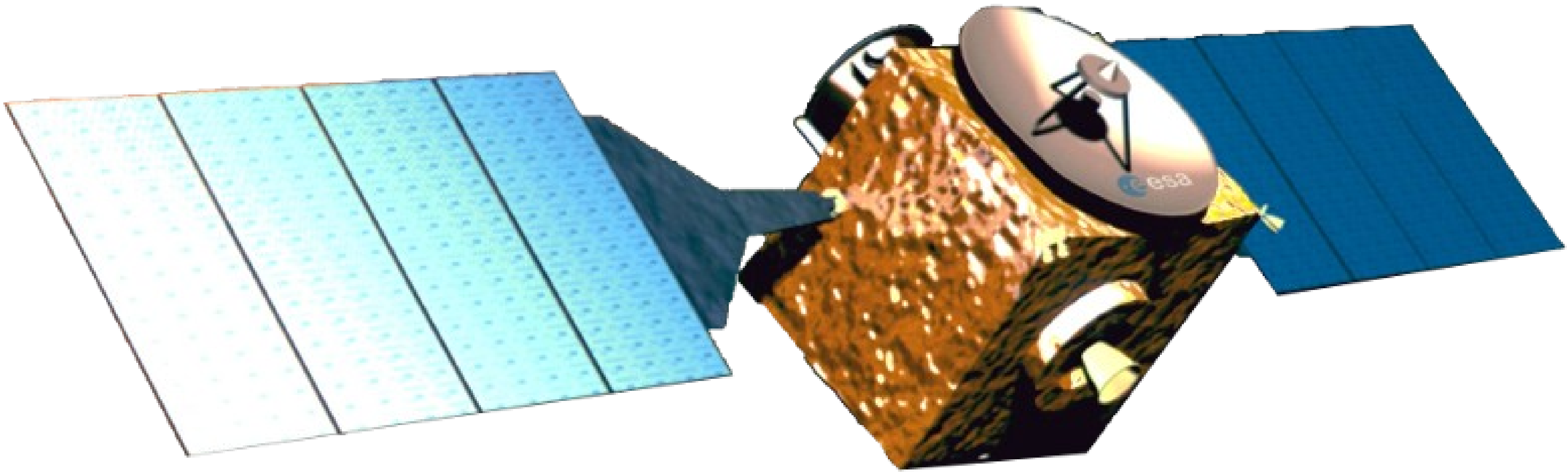
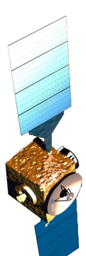
2011





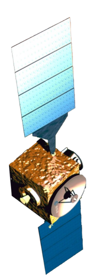
# Mars Express - MEX



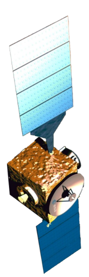
# Mars Express – MEX

- Mars orbiter probe
- Launched and managed by ESA
- Launch: June 3 2003 from Baykonur with a Soyuz rocket
- Still in operation
- Power: 460W
- Mass: 666 kg + 457 kg of fuel



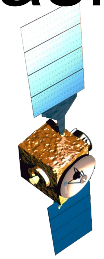
# MEX scientific payload

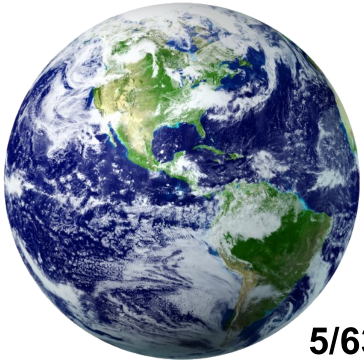
- Surface and subsurface exploration
  - **HRSC** (High Resolution Stereo Camera) – stereo camera combined with hi-res camera
  - **OMEGA** (Visible and Infrared Mineralogical Mapping Spectrometer) – spectrometer working in visible and infrared spectrum
  - **MARSIS** (Sub-surface Sounding Radar Altimeter) – up to 5 km of depth
- Atmosphere and ionosphere exploration
  - **PFS** (Planetary Fourier Spectrometer)
  - **SPICAM** (Ultraviolet and Infrared Atmospheric Spectrometer)
  - **ASPERA** (Energetic Neutral Atoms Analyser)
- Other
  - **MaRS** (Mars Radio Science Experiment) – Uses radio signals to investigate atmosphere, surface, subsurface, gravity and solar corona density during solar conjunctions. It uses the communications subsystem itself.



# MEX – Beagle 2

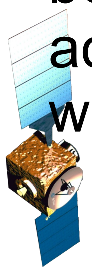
- Separate landing module carried by MEX
- Laboratory searching for life
- Crashed





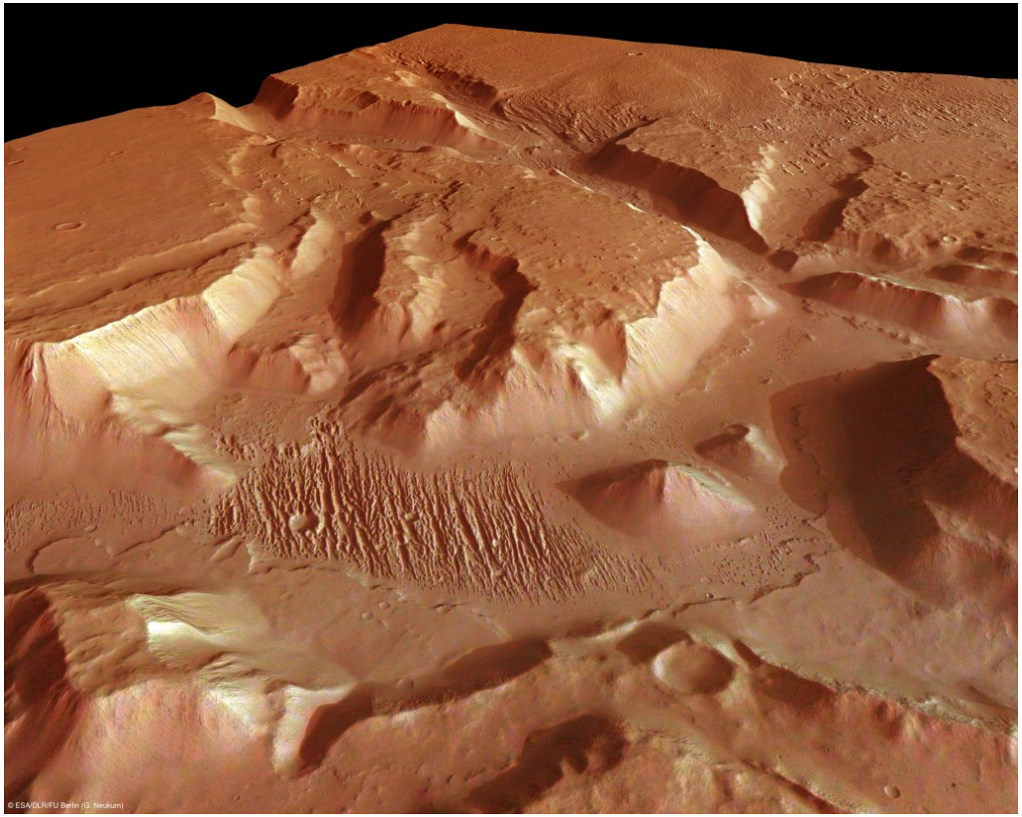
# MEX discoveries

- 2004
  - January 23
    - Discovery of water ice in the South Polar ice cap
  - March 30
    - A press release announces that the orbiter has detected methane in the Martian atmosphere.
  - July 15
    - MEX discovered the spectral features of the compound ammonia in the Martian atmosphere. Just like methane discovered earlier, ammonia breaks down rapidly in Mars' atmosphere and needs to be constantly replenished. This points towards the existence of active life or geological activity; two contending phenomena whose presence so far have remained undetected.

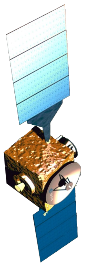


# MEX discoveries

- 2007
  - February 23
    - The High Resolution Stereo Camera (HRSC) has produced dramatic images of key tectonic features in Aeolis Mensae.

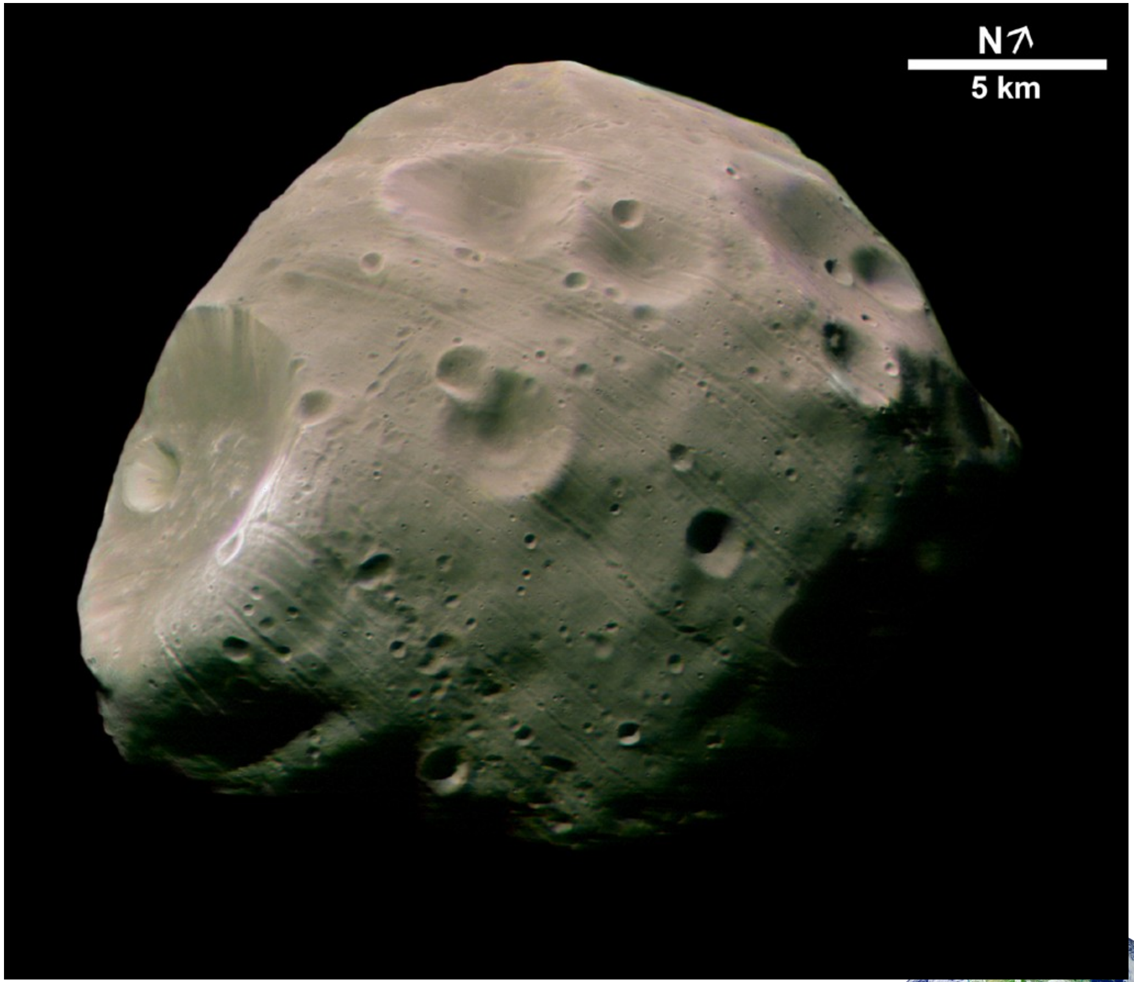


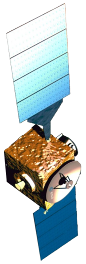





# MEX discoveries

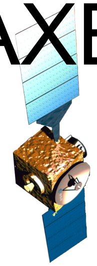
- 2010
  - March 5
    - Flyby of Phobos to try to measure Phobos's gravity



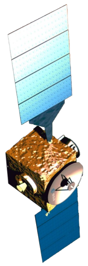
# Report outline

- Earth-Mars communication problems
- MEX data description
- MEX communication problems
- MEXAR – a tool for downlink planning
  - architecture
  - problem definition, algorithm
- Different demands of uplink
- RAXEM – a tool for uplink planning

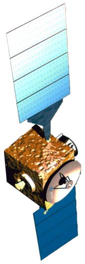

# How to communicate?

- There is no permanent and interactive connection with the probe!
- The Earth-Mars distance ranges from 54.6 million km to 401 million km
- Thus, the information travelling at the speed of light arrives 3 – 23 minutes later



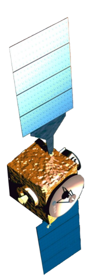
# How to communicate?

- There is no permanent and interactive connection with the probe!
- The probe orbits Mars -> some half of the time the Earth is just not directly visible (eclipse)
- Mars and Earth orbit the Sun -> sometimes the Earth isn't visible from Mars' surroundings
- Occasionally, the moons and other space bodies can disturb the communication

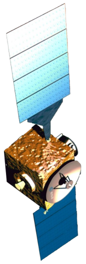

# How to communicate?

- There is no permanent and interactive connection with the probe!
- What's more – MEX is a Single Pointing System
    - it either points to Mars and acquires the data
    - (x)or it points to Earth and can send/receive data

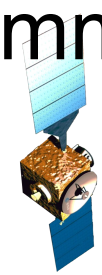

# How to communicate?

- There is no permanent and interactive connection with the probe!
- The ground receivers/transmitters are shared among a number of space projects and sometimes they just cannot be concentrated on MEX all the available time



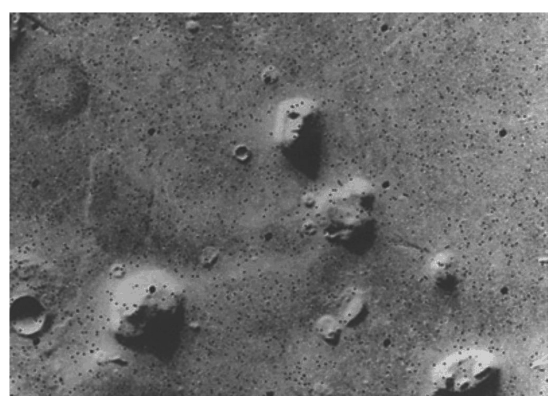
# Uplink/downlink windows

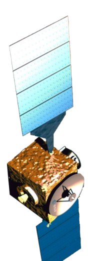
- The time range when receiving of MEX's data is possible and all systems are ready for it is called a **dowlink window**
- Similarly, an **uplink window** is the time when it is possible to transmit commands to the probe
- Both up- and downlink windows can be (almost) precisely computed in advance
- There are cases with 40 days without a communication window!

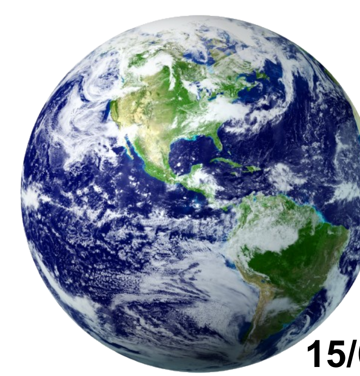


# What are the data?

- MEX has been equipped with 7 scientific instruments – the „payload“
- Each instrument measures, captures or acquires data
- Eg. High Resolution Stereo Camera photographs the surface of Mars

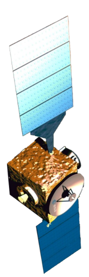






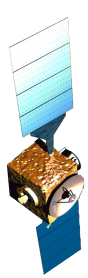
# What are the data?

- MEX not only captures data, it also generates data
  - validation reports
  - state information
  - logs
  - monitoring information
- These data are called **housekeeping data**

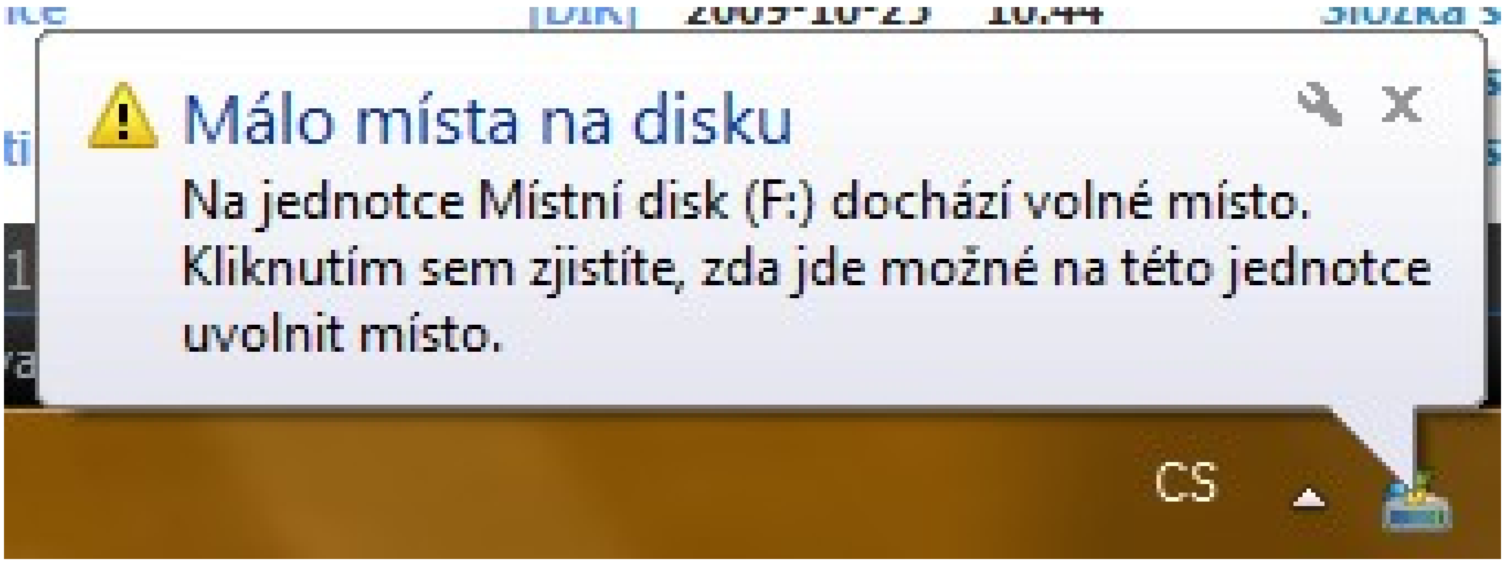

# How are the data stored?

- There is a single on-board data storage called Solid State Mass Memory (SSMM)
  - stores both types of data (scientific and housekeeping)
- SSMM is subdivided into **packet stores**, which are blocks of constant size and a given priority
- It is a large „cache“ for delaying the data until they can be sent to Earth



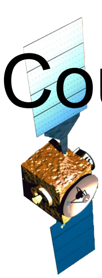
Recently, SSMM had a failure and seems to be broken, so scientists search a way how to work even without it. And they're on their way to succeed.

# Disk full???


Málo místa na disku
Na jednotce Místní disk (F:) dochází volné místo.
Kliknutím sem zjistíte, zda jde možné na této jednotce uvolnit místo.
CS

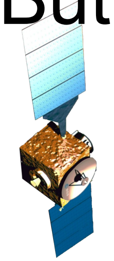
# Disk full???

- What to do, when the SSMM is full, new data need to be stored and old data cannot be sent to Earth?
- Rewrite some old low-priority data!
- Housekeeping cannot be overwritten (essential for the existence and diagnostics of the probe)
- Therefore some scientific data are lost!
  - What a pity!
  - Couldn't we do something against it?

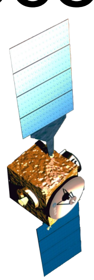
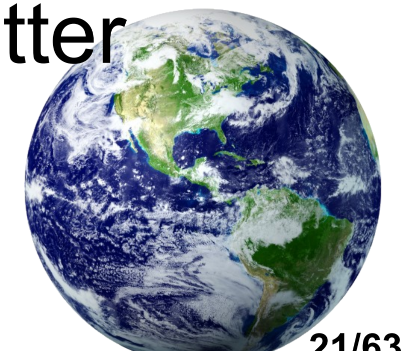

# Disk full???

- The solution that prevents from scientific data loss is good downlink planning!
  - Cannot guarantee 0% data loss, but can guarantee to lose the very minimum
- The Mission Planing team knows this
  - So they assembled downlink plans manually
  - It was a hard job, all the people were overloaded with work
  - But their work had reasonable results

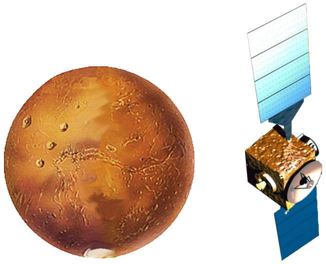

# MEXAR

- Mars EXpress ARchitecture
- A Java tool developed by a team of AI scientists since 2000
- Targets MEX data downlink planning (MEX Memory Dump Problem - MEX-MDP)
- Was never used (and never will be)!
- People from Mission Planning didn't trust a piece of software could help them do better

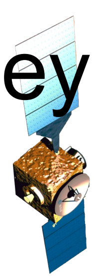
# MEXAR

- Why was MEXAR never used?
  - Because it wasn't tested on real mission data
    - Well, there were no mission data before the probe launch
  - Sounds like a magic circle?
    - Maybe, but a solution still exists



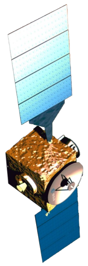
# MEXAR2

- The development team took data from the first 6 months of MEX operation and fed MEXAR with them
- They simulated generating plans on these data
- And the results were surprising!
- They went even further – they optimized MEXAR on these real data and gave birth to MEXAR2
- They introduced MEXAR2 to Mission Planning



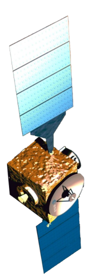
# MEXAR2 architecture

- Problem Solver
  - based on AI techniques
  - solves the MEX Memory Dump Problem
- Interaction Module
  - user interface to the solver
  - inspection over the solution
  - change the result according to strategic decisions



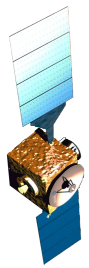
# MEXAR2 tasks

- The main task is to quickly compute a good solution to MEX-MDP
- In addition it is needed to be able to quickly adjust a solution just before the downlink window starts to reflect the expected/real data size differences
  - the size of compressed data cannot be predicted very well


# MEXAR2 resources

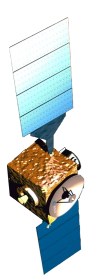
- SSMM (the sotrage)
  - has a limited capacity
- communication channel
  - a set of downlink windows
  - every window can have different data rate



# MEXAR2 activities

- store operation
  - save some acquired data to SSMM
- memory dump operation
  - transfer the given amount of data from the given packet store to Earth

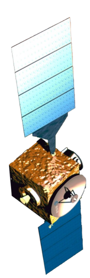
- all activities have a fixed duration, and have their start and end time


Memory Dump Problem

# MEX-MDP definition

- A single MEX-MDP instance is composed of a set of scientific observations, a set of housekeeping productions, and a time horizon H = [0, H]. The solution to a MEX-MDP is a set of dump commands $S=\{md_1, md_2, \ldots, md_n\}$ such that:
  - At each instant of $t \in H$, the amount of data stored in each packet store does not exceed the packet store capacity, i.e., overwriting is not allowed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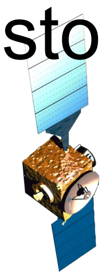
  - The whole set of data is 'available' on the ground within the considered temporal horizon H=[0, H], except an amount of residual data for each packet store lower or equal to its capacity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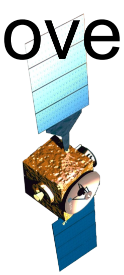
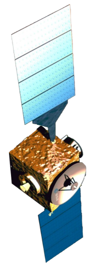
  - Each dump activity is executed within an assigned time window which has a constant data rate. Additionally, dump commands cannot mutually overlap.



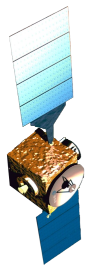
# MEX-MDP another constraints

- Some more constraints apply to all solutions of MEX-MDP
  - housekeeping data have to be all dumped before the day's end, whereas science data don't have to
  - every packet store has to be downloaded as a whole (without preemption)



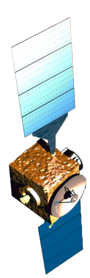
# MEX-MDP objective function

- To find a high quality solution
  - To maintain all the constraints
  - Small plan (in the number of dump activities)
  - Robust plan
  - Satisfy priorities
  - Absorb external modifications by human operators

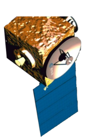

# MEX-MDP computation abstraction

- Two levels of abstraction in the algorithm
  - Data dump level
    - assesses the amount of data to dump from each packet store during each time window
  - Packet level
    - starting with the results of the previous level, generates the final dump commands
    - no problem to generate fully automatically once we have a result from Data dump level

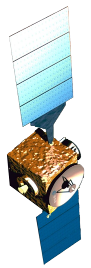

# MEX-MDP algorithm

```
Input: Problem P, parameters robust, priority
Output: Downlink commands Cmd
//Data dump level
Solution S <- empty solution; //a partial solution
while (S incomplete) do
  S <- HouseKeepingAllocation(P, priority);
  S <- MaxFlowAllocation(P, S, robust, priority);
  if (no more HouseKeeping allocation) then
    break;
//Packet level
Cmd <- GenerateDownlink(S, priority);
return Cmd;
```



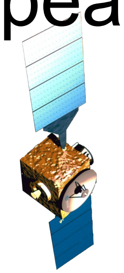
# MEX-MDP algorithm

- HouseKeepingAllocation
  - Finds a consistent solution for housekeeping packet stores
    - Need to avoid preemption and residual data
  - Backtracking, on each call generates one possible solution (each call does one backtracking step to a leaf)
  - If some data have to be overwritten, the *priority* parameter specifies which data to override



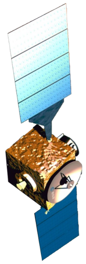
# MEX-MDP algorithm

- MaxFlowAllocation
  - Finds a solution for the scientific data
  - Reduces problem P with the partial solution S from previous step to a max-flow-finding problem – problem P has a solution iff the max flow in the reduced problem is >= the amount of data to dump
  - Copes with the robustness parameter – the more robust the solution should be, the more 'free capacity' is available to cover unexpected data flow peaks


# MEX-MDP algorithm

- GenerateDownLink
  - Sorts the dumps according to their stores' priorities
  - Generates the final commands to be executed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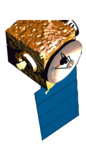
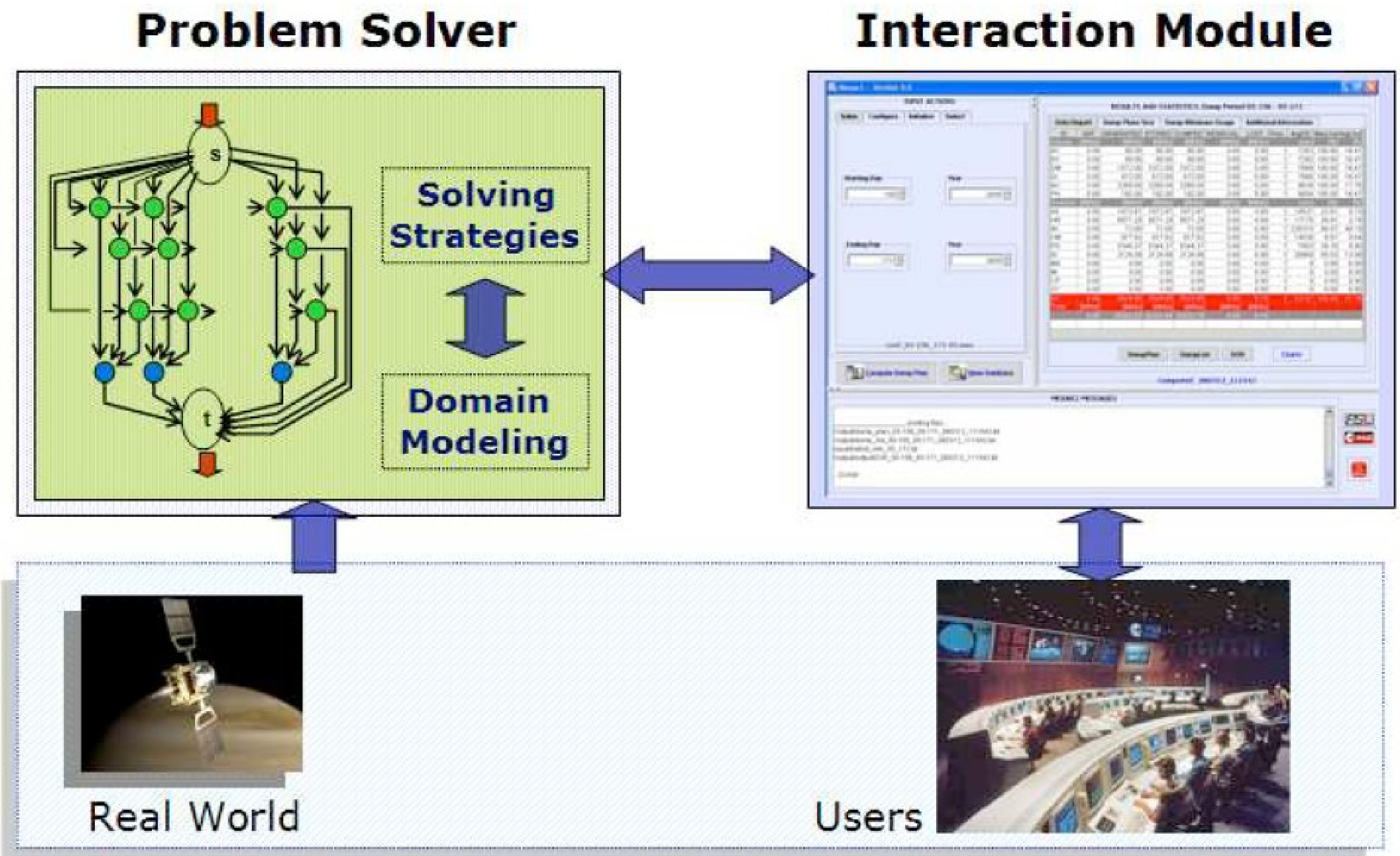
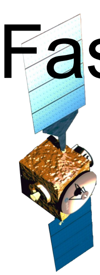


# MEXAR2 Interaction Module



# MEXAR2 Interaction Module

- Two basic aims:
  - To reproduce the usual problem solving cycle of real users, collecting in a unique tool all features and functionalities to guarantee the traditional problem solving style
  - To allow to exploit the domain expert abilities and foster the involvement and contribution to the problem solving
- Developed using iterative design process
  - Fast development cycles, a lot of consultations


# MEXAR2 Interaction Module

Solver

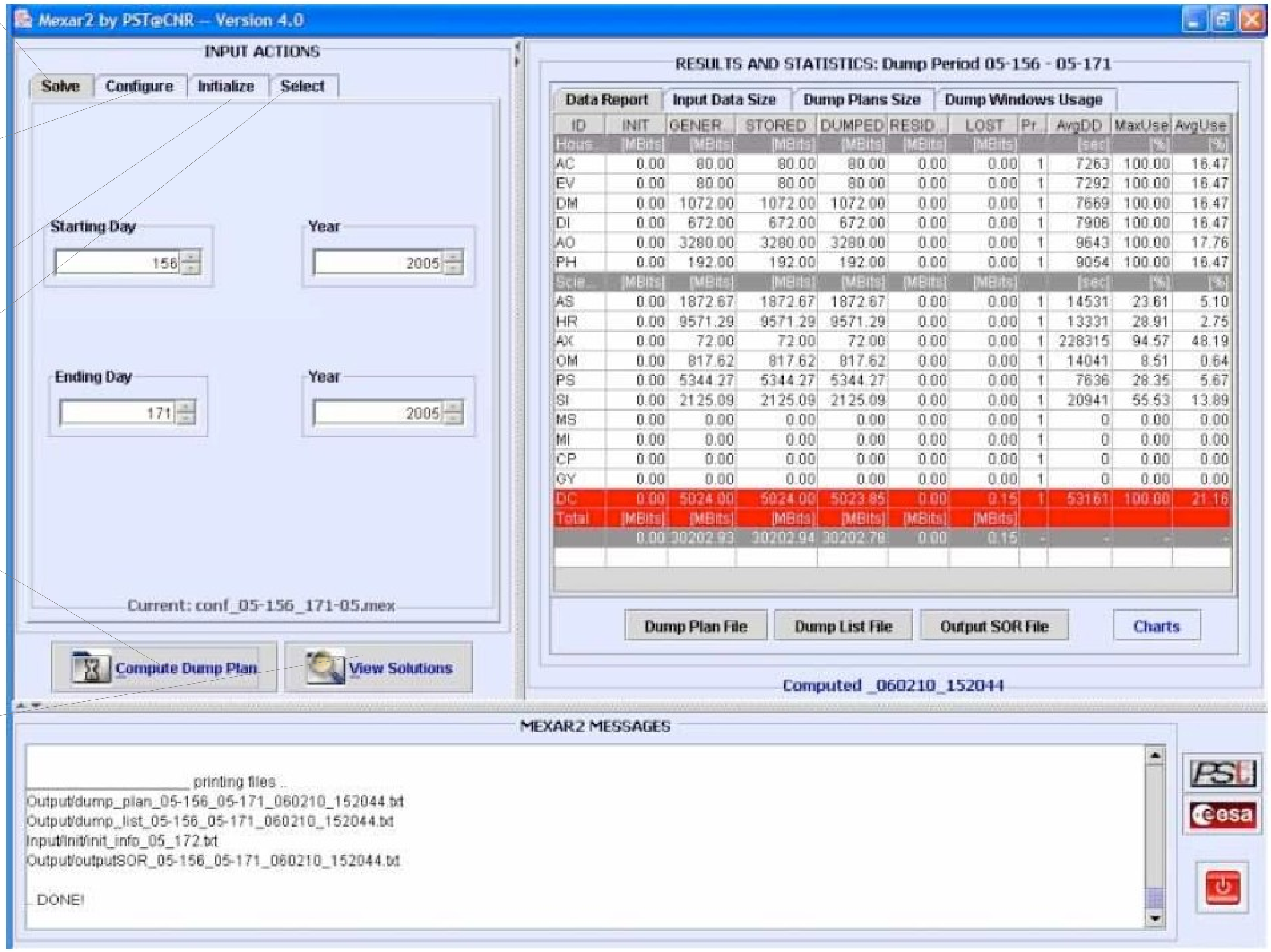
Configure

Initialization

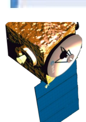
Select

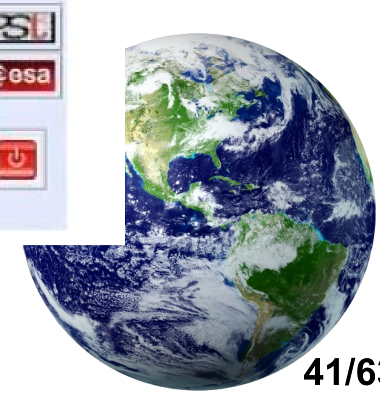
Compute Dump Plan

View Solutions




| ID | INIT | GENER.. | STORED | DUMPED | RESID.. | LOST | Pr.. | AvgDD | MaxUse | AvgUse |
|---|---|---|---|---|---|---|---|---|---|---|
| Hous.. | [MBits] | [MBits] | [MBits] | [MBits] | [MBits] | [MBits] | | [sec] | [%] | [%] |
| AC | 0.00 | 80.00 | 80.00 | 80.00 | 0.00 | 0.00 | 1 | 7263 | 100.00 | 16.47 |
| EV | 0.00 | 80.00 | 80.00 | 80.00 | 0.00 | 0.00 | 1 | 7292 | 100.00 | 16.47 |
| DM | 0.00 | 1072.00 | 1072.00 | 1072.00 | 0.00 | 0.00 | 1 | 7669 | 100.00 | 16.47 |
| DI | 0.00 | 672.00 | 672.00 | 672.00 | 0.00 | 0.00 | 1 | 7906 | 100.00 | 16.47 |
| AO | 0.00 | 3280.00 | 3280.00 | 3280.00 | 0.00 | 0.00 | 1 | 9643 | 100.00 | 17.76 |
| PH | 0.00 | 192.00 | 192.00 | 192.00 | 0.00 | 0.00 | 1 | 9054 | 100.00 | 16.47 |
| Scie.. | [MBits] | [MBits] | [MBits] | [MBits] | [MBits] | [MBits] | | [sec] | [%] | [%] |
| AS | 0.00 | 1872.67 | 1872.67 | 1872.67 | 0.00 | 0.00 | 1 | 14531 | 23.61 | 5.10 |
| HR | 0.00 | 9571.29 | 9571.29 | 9571.29 | 0.00 | 0.00 | 1 | 13331 | 28.91 | 2.75 |
| AX | 0.00 | 72.00 | 72.00 | 72.00 | 0.00 | 0.00 | 1 | 228315 | 94.57 | 48.19 |
| OM | 0.00 | 817.62 | 817.62 | 817.62 | 0.00 | 0.00 | 1 | 14041 | 8.51 | 0.64 |
| PS | 0.00 | 5344.27 | 5344.27 | 5344.27 | 0.00 | 0.00 | 1 | 7636 | 28.35 | 5.67 |
| SI | 0.00 | 2125.09 | 2125.09 | 2125.09 | 0.00 | 0.00 | 1 | 20941 | 55.53 | 13.89 |
| MS | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1 | 0 | 0.00 | 0.00 |
| MI | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1 | 0 | 0.00 | 0.00 |
| CP | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1 | 0 | 0.00 | 0.00 |
| GY | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1 | 0 | 0.00 | 0.00 |
| DC | 0.00 | 5024.00 | 5024.00 | 5023.85 | 0.00 | 0.15 | 1 | 53161 | 100.00 | 21.16 |
| Total | [MBits] | [MBits] | [MBits] | [MBits] | [MBits] | [MBits] | | | | |
| | 0.00 | 30202.93 | 30202.94 | 30202.78 | 0.00 | 0.15 | - | - | - | - |

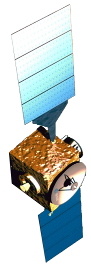




Sorry for the low quality, no better screen is available

# MEXAR2 workflow

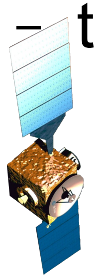
- Select the time interval of interest in *Input actions - > Solve*
- Specify the packet stores, their sizes and priorities in *Input actions - > Configure*
- Specify the residual data from previous days in *Input actions - > Initialize*
- Specify parameters of the solver in *Input actions - > Select*
- *Compute Dump Plan*
- Some feedback appears on *Message pane* (eg. the fragmentation of the downlink) – the user can specify some thresholds to avoid short commands or commands dumping a small amount of data
- Inspect the results in *Results and Statistics*
  - Statistics, data balance, the division of packet stores and so
- Reorder the generated plan



# MEXAR2 Continuous Operation

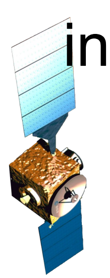
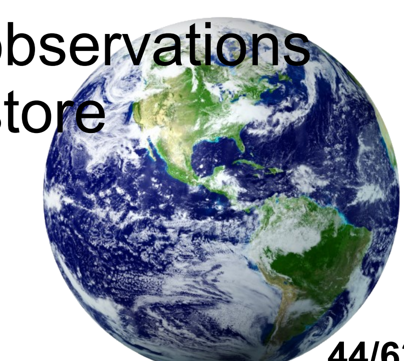
Payload Operation Requests
- specifications of what to download

- MEXAR2 accepts PORs and downlink windows specification from the Mission Planning System
- The solver solves the problem and returns a solution
- The mission planners reorder the plan by their strategic decisions
  - Some data are requested to arrive on time or by a specified deadline
    - the algorithm doesn't handle these requests


# MEXAR2 evaluation

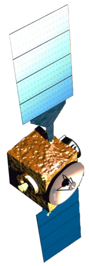
- Main objectives – minimal data loss, plan size, robustness, maintaining priority
- Test data – four real data sets from the first six months of MEX operation – B1, B2, B3, B4 (B1 is the most complex one)
- The performance was tested on a 440 MHz Sparc with 256 MB RAM
  - Two settings – S1, S2
    - S2 uses a min-threshold to group small payload observations into one bigger and stores it into a single packet store

# MEXAR2 evaluation

Table 1: Volume of data generated [Mbits] vs. overall channel dump capacity [Mbits]

| Benchmark | N.Days | Volume Generated (VG) | Dump Capacity (DC) | VG/DC |
|---|---|---|---|---|
| B1 | 31 | 78323.4 | 98268.1 | 0.80 |
| B2 | 19 | 71938.6 | 114566.1 | 0.63 |
| B3 | 14 | 22763.0 | 125516.2 | 0.18 |
| B4 | 15 | 30747.2 | 155412.7 | 0.20 |

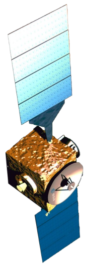


# MEXAR2 evaluation

Table 2: Performances on S1 and S2 data. S2 differs for additional threshold settings

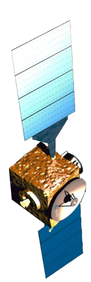
| | Benchmark | Stored | Dumped | Residual | Lost | Nstores | AvgPlanSize | MaxSize | Time (secs) |
|---|---|---|---|---|---|---|---|---|---|
| **S1** | B1 | 78323 | 78323 | 0 | 0 | 1534 | 17.8 | 57 | 209 |
| | B2 | 71938 | 71938 | 0 | 0 | 1314 | 22.9 | 32 | 323 |
| | B3 | 22763 | 22763 | 0 | 0 | 605 | 16.7 | 33 | 7 |
| | B4 | 30747 | 30747 | 0 | 0 | 850 | 23.7 | 32 | 22 |
| **S2** | B1 | 78323 | 78323 | 0 | 0 | 838 | 17.3 | 34 | 22 |
| | B2 | 71938 | 71938 | 0 | 0 | 688 | 22.5 | 33 | 12 |
| | B3 | 22763 | 22763 | 0 | 0 | 334 | 16.2 | 29 | 4 |
| | B4 | 30747 | 30747 | 0 | 0 | 399 | 20.1 | 27 | 8 |

- The use of thresholds is a contribution of MEXAR2 to mission planners (S2 is much better)

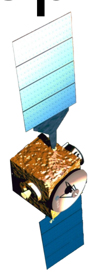

# MEXAR2 interaction evaluation

- Evaluating the GUI and its usability
- Iterative development with heuristic evaluation between periods to reveal bugs and things to make better
- Heuristic evaluation – team of experts and users judges the compliance to usability principles

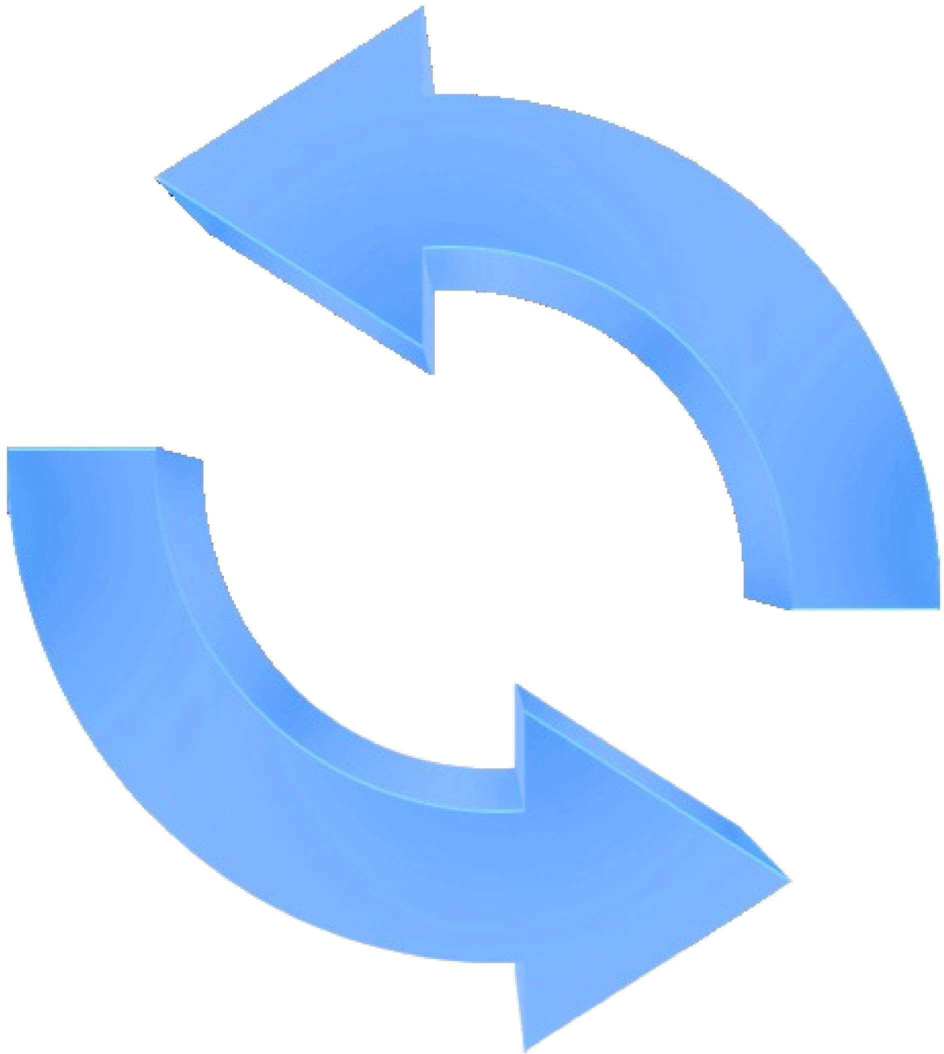



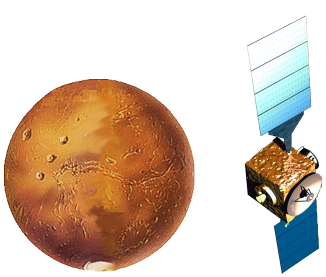

# MEXAR2 Results

- Quicker, shorter and high quality data dump plans
- Saved 50% of time for producing plans
- Minimized data loss (due to the ability to generate plans for multiple days quickly)
- Speeded up the data delivery to Earth
- The mission planning personnel lost its skepticism to a new tool

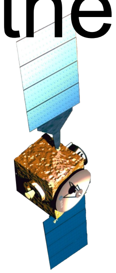

# What about the opposite direction?





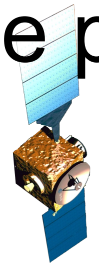
# Different demands on uplink

- Limited on-board command buffer size
  - 3000 commands
- Need to guarantee safe delivery
- The end of each uplink session must provide commands to set the probe to the mode for communicating with Earth (instruments turned off, antenna to the Earth) in order to prevent probe losing in case of problems with sending of the next commands

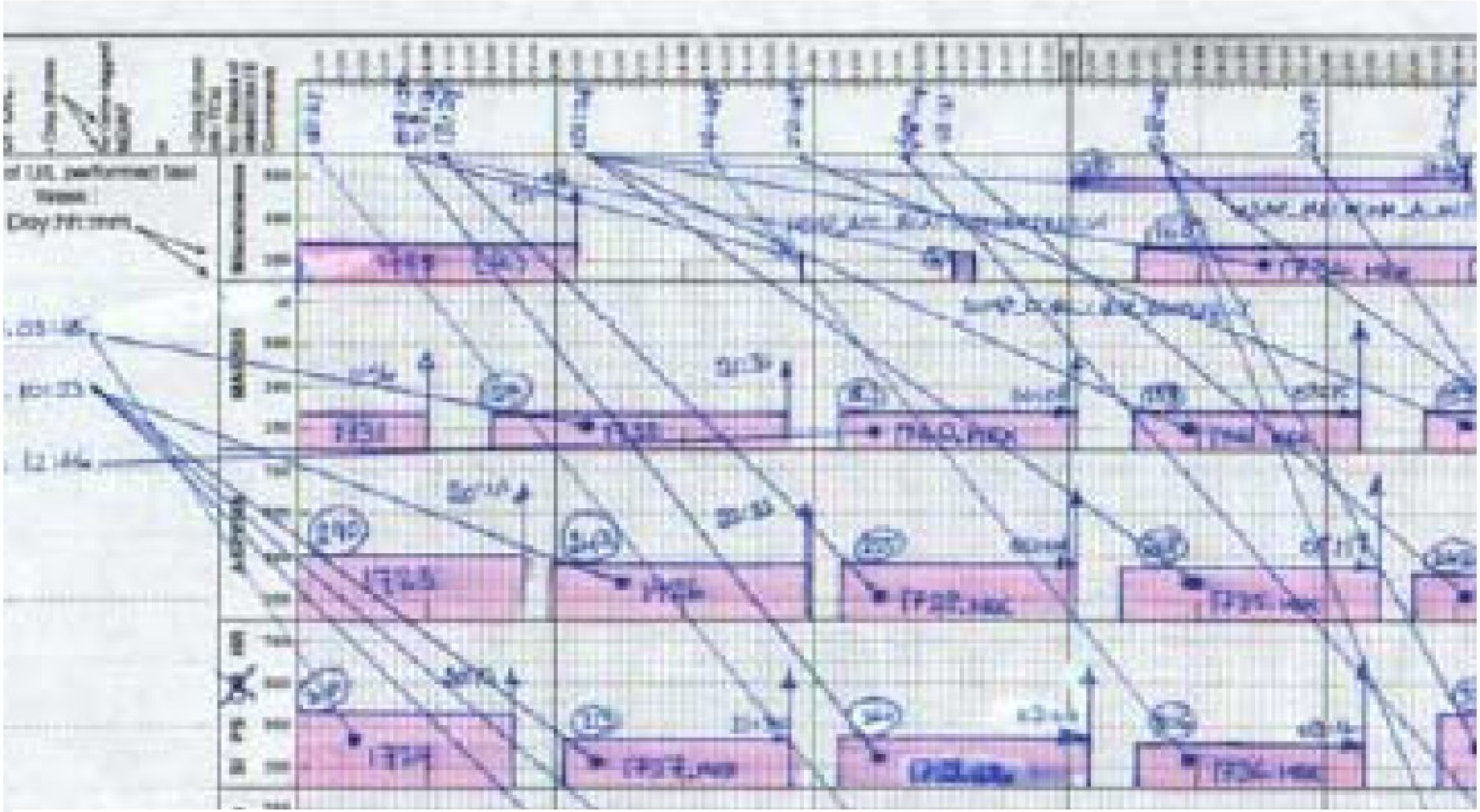




# Uplink rules

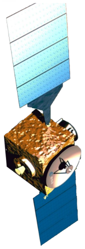
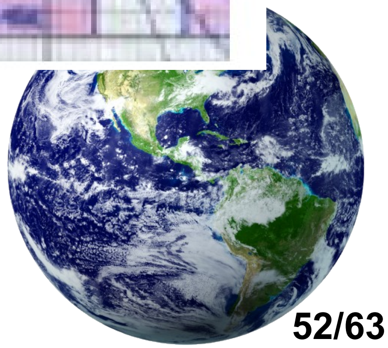
- Commands executed earlier should upload earlier
- Some commands have higher priority
- Full confirmation where possible
  - except short windows, low-power eclipse seasons, long light-travel time
- A backup uplink is planned on a different ground station
- The plans are computed one week to the future


# Let's do it! Manually...

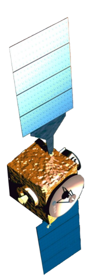


An example Olligram

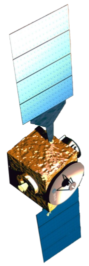
# Olligrams

- Uplink times are connected with execution times, backup windows computed separately
- Survived for 3 years of operation
- Replanning was very time-consuming
- Named after one engineer


# Let's do it better! RAXEM!

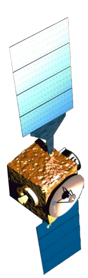
- A Java tool inspired by the success of MEXAR2
- Aids spacecraft engineers to plan uplink commands
- In operational use since 2007
- RAXEM is MEXAR typed reversed to show the correlation to that tool
  - The same team developed both MEXAR and RAXEM


# RAXEM architecture

- Problem Solver
  - AI-based solver of the planning problem
- Interaction Module
  - Manages uplink database
  - SIFs management and generation (SIF is a basic unit of uplink, comprises of several MDAFs and the planning information)
  - Active user participation on the resulting plan

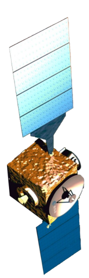
A file containing
a set of commands


A file containing
a set of commands

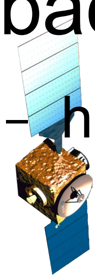
# RAXEM inputs

- Old MDAFs in order to reconstruct the command buffer
- Current MDAFs to upload
  - These files are given flags
    - Backup window – the position and time of the backup window
    - Full confirmation – need it or not?
- A list of uplink windows (autogenerated)

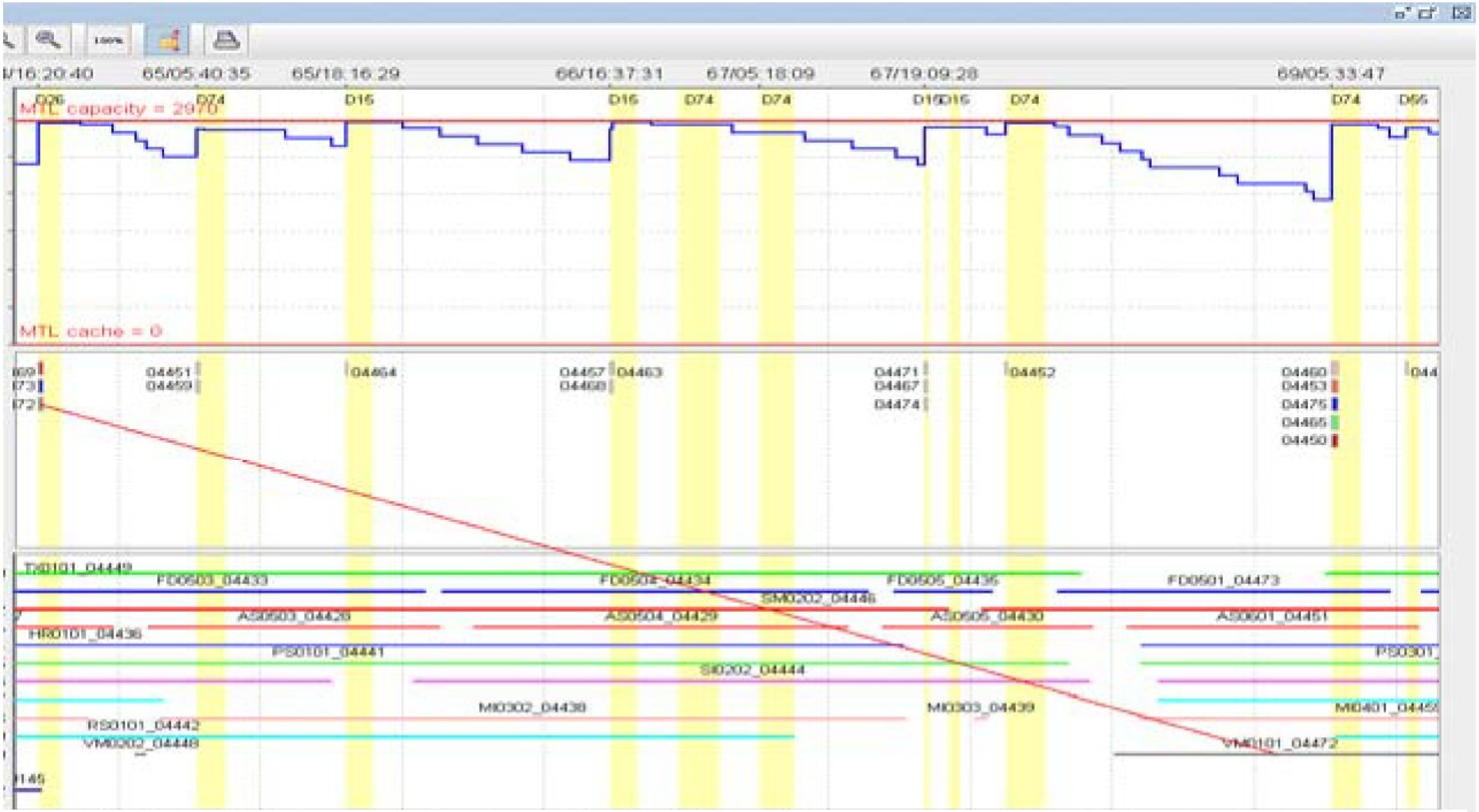


# RAXEM algorithm

- Sorry, they didn't publish any information, but it should be some kind of prioritized scheduler
- If the algorithm fails to find a solution, it relaxes the flags – first backups, then confirmation
- If it still fails, it selects MDAFs not to be uploaded and alerts the user
  - It offers splitting some MDAFs into several smaller which could possibly help
- If even this doesn't help, just drops some MDAFs (a rollback mechanism is implemented in MEX)
  - has never occured

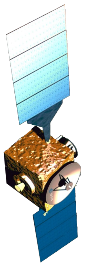

# RAXEM output

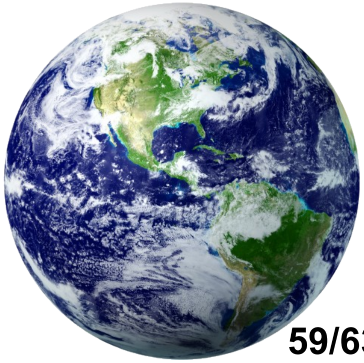



A better-looking (and interactive!) Olligram

# RAXEM Interaction Module

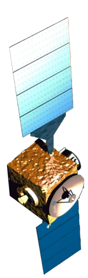
- The interaction module was developed using the same iterative design process as MEXAR
  - The ESA people were very glad for this





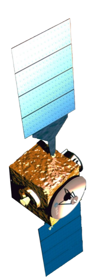
# RAXEM results

- Shortened the planning from hours to minutes
- Allows what-if analyses
- Error-free
- Prevents MEX from being workless :)



# Conclusion

- Mixed initiative AI techniques proved as being highly usable in proffessional and critical use cases
  - The AI part does the boring part which would take hours of manual work
  - The people make the interesting part (strategic) which is much simpler for them than for AI (yet?)


# Credits

- MEXAR ( http://www.stsci.edu/institute/conference/iwpss/plenary-I1-cesta.pdf )
  - Amedeo Cesta, Gabriella Cortellessa, Simone Fratini, Angelo Oddi, Nicola Policella
    - National Research Council of Italy, Institute for Cognitive Science and Technology
- RAXEM ( http://smc-it.org/2009/iwpss/papers/4.pdf )
  - Erhard Rabenau
    - NOVA Space Associates Ltd
  - Alessandro Donati, Michel Denis, Nicola Policella
    - European Space Operations Centre
  - Amedeo Cesta, Gabriella Cortellessa, Angelo Oddi, Simone Fratini, Guilio Bernardi
    - National Research Council of Italy, Institute for Cognitive Science and Technology



# Thank you!


FACE ON MARS
OVERLAYS - VIKING SOURCED SHADING - THE HIDDEN RECORDS . COM
SOURCE - NASA/JPL/UNIVERSITY OF ARIZONA