TU5

ICAPS 2006

The English Lake District, Cumbria, UK

Tutorial on Planning activities for Earth watching and observation satellites and constellations: from off-line ground planning to on-line on-board planning

Gerard Verfaillie
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Preface

Planning activities such as detection, observation, data memorization, analysis, and downloading for Earth watching and observing satellites is a challenging application of automated planning and scheduling techniques.

Since the first Earth observation satellites, this task has evolved from handmade plans to entirely automatically generated ones. It has also evolved from plans built off-line on the ground in mission centers under the supervision of human operators to plans built on-line on-board each satellite. It has finally evolved from the management of one satellite to the centralized or distributed management of constellations of satellites. In addition, the ability to perform on-board detection and data analysis added reactivity requirements. On the other hand, the abilities of the new satellites in terms of attitude agility offered more observation opportunities, but made the planning activity far more complex. The future Earth watching and observation satellites will be autonomous intelligent cooperative robots.

The objective of this tutorial is first to present all the features of this challenging domain, then to show how planning problems can be stated (degrees of freedom, physical constraints, user soft and hard requirements) using frameworks such as graph theory, integer programming, constraint programming, scheduling and planning models, and finally to show how they can be automatically solved using various techniques such as greedy search, local search, tree search, or dynamic programming.

Tutorial outline:

- *Some physical facts about Earth observing satellites*
- *How they are or could be managed*
- *How the management problem can be stated*
- *How it can be solved*
- *Results from experiments and practice*
- *A glance at the near and far future*

Instructors

- *Gérard Verfaillie graduated from Ecole Polytechnique (Paris) in 1971 and from SUPAERO (Ecole Nationale Superieure de l'Aeronautique et de l'Espace, French national engineering school in aeronautics and space, computer science specialization) in 1985. Since 1986, he has been working as a research engineer at ONERA (Office National d'Etudes et de Recherches Aerospatiales, French government aerospace research center), in the computer science department, and then in the automatic control department. He has been working from 2003 to 2005 as a research supervisor at LAAS/CNRS (Laboratoire d'Analyse et d'Architecture des Systemes, Centre national de la recherche Scientifique, Systems analysis and architecture laboratory, French national research center). His research activity is related to models, methods, and tools for combinatorial optimization and constrained optimization, especially for planning and decision-making. They take place at the crossing between Operations Research and Artificial Intelligence. He carried out studies for CNES (Centre National d'Etudes Spatiales, French space* *agency), ESA (European Space Agency), Astrium or Airbus. He has been entitled to supervise academic research since 1997 and teacher at SUPAERO since 1998.*

- *Michel Lemaitre is a research engineer, graduated from ENSEEIHT (Ecole Nationale Superieure d'Electrotechnique, d'Electronique, d'Informatique, d'Hy-drauli-que et des Telecommunications, Toulouse, France) in 1972. He completed a PhD degree in 1975 at LAAS/CNRS (Laboratoire d'Analyse et d'Architecture des Systemes, Toulouse, France). From 1976 he worked at ONERA in Data Bases, Software Engineering and Reactive Systems. Since 1996, his current research interests include Constraint Programming, Algorithmics, and Decision Theory. He was involved in several studies with CNES (Centre National d'Etudes Spatiales) concerning mission planning and scheduling for Earth Observation Satellites (SPOT and Pliades systems). He is currently involved in a joint ONERA/CNES research program on autonomy in space, and supervises a PhD student on fair allocation of satellite resources. He teaches at SUPAERO (Ecole Nationale Suprieure de l'Aeronautique et de l'Espace).*

Planning activities for Earth watching and observing satellites and constellations:

From off-line ground planning to on-line on-board planning

Gérard Verfaillie and Michel Lemaître
ONERA, Toulouse, France

ftp://ftp.cert.fr/verfaillie/ICAPS06-tutorial

ICAPS Tutorial, Planning activities for Earth watching and observing satellites and constellations, Cumbria, UK, June 2006

Tutorial outline

1. **Some physical facts about Earth observing satellites**.
2. **How they are or could be managed**.
3. **How the management problem can be stated**.
4. **How it can be solved**.
5. **Results from experiments and practice**.
6. **A glance at the near and far future**.

Some physical facts about Earth observing satellites

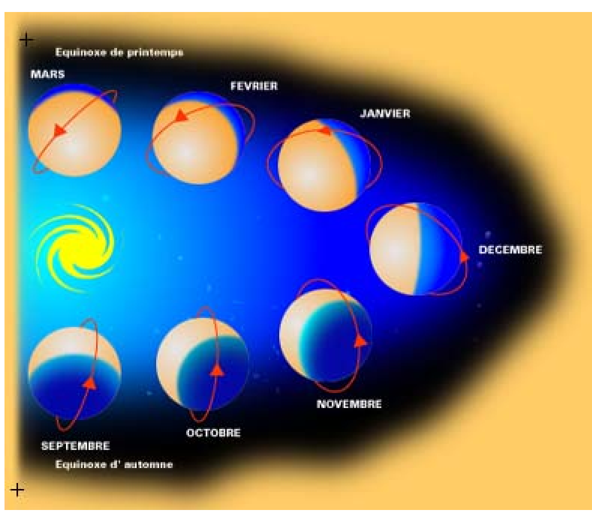
The orbit (1)

Usually: **circular**, **quasi-polar**, and **heliosynchronous** orbit.

Low altitude: some hundreds of kilometers (700-800 km).

Alternance of **day** and **night periods**.

Always the **same local hour** when passing the equator.

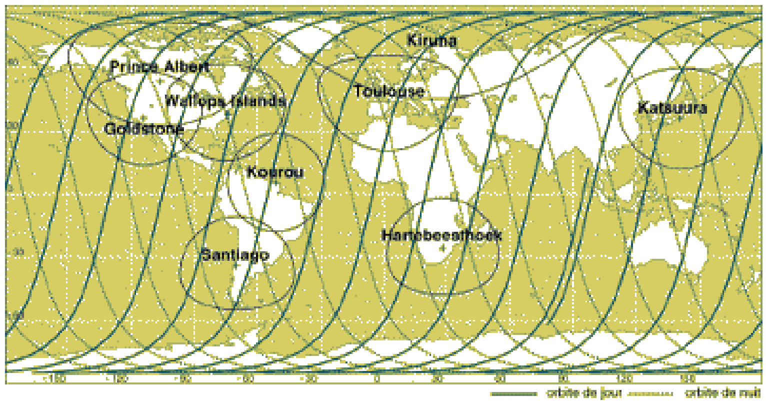


The orbit (2)

Track of the satellite **over one day**, because of the **rotation** of the Earth on itself.

Distance between **two successive tracks** at the equator: some thousands of kilometers.

Complete cycle: some tens of days.



The platform

Maintenance of the satellite on its **reference orbit**: regular **orbital manoeuvres** via **ergol thrusters**.

Attitude control: see further.

Energy production via **solar panels**.

Energy storage via **batteries**.

Communication with the ground via **low-rate antennas**.

Communication only when the satellite is in **visibility** of a **ground station**: around 10% of the time.

The payload

One or several **observation instruments**.

Optical, **infra-red**, or **radar**, eventually **multi-spectral**.

Various **resolutions**, until sub-metric ones.

Various **swaths** on the ground, from some hundreds of kilometers until some kilometers.

Mass memory to store data before **downloading** them via **high-rate antennas**.

Non agile (optical) satellites (1)

Example: the French **SPOT** family.

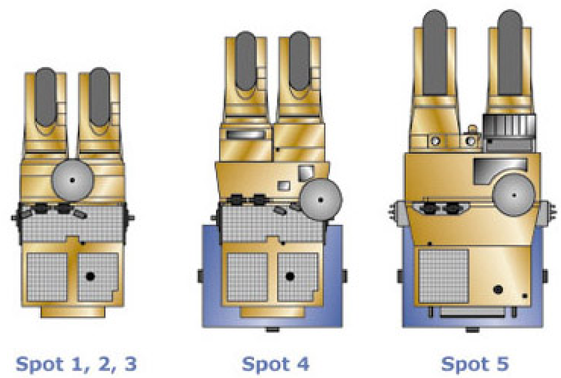
© CNES-mars 2002/Illust. D. Ducros

Non agile (optical) satellites (2)

Maintenance of the satellite in a **geocentric attitude**.

One degree of freedom in terms of observation via a **mobile mirror** in front of each instrument.

The Spot satellites seen from below:

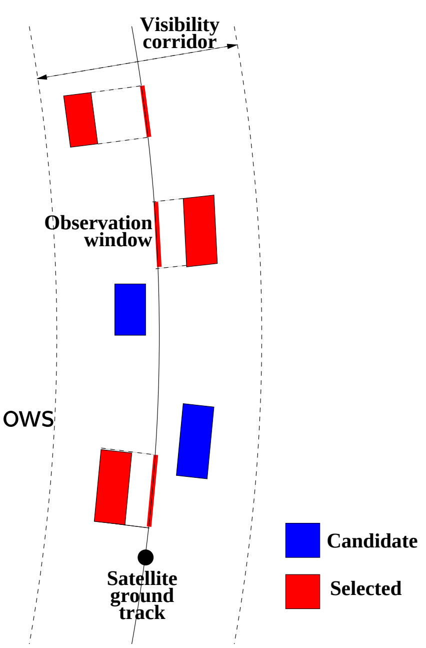


Non agile (optical) satellites (3)

Possible **sequence of observations**:

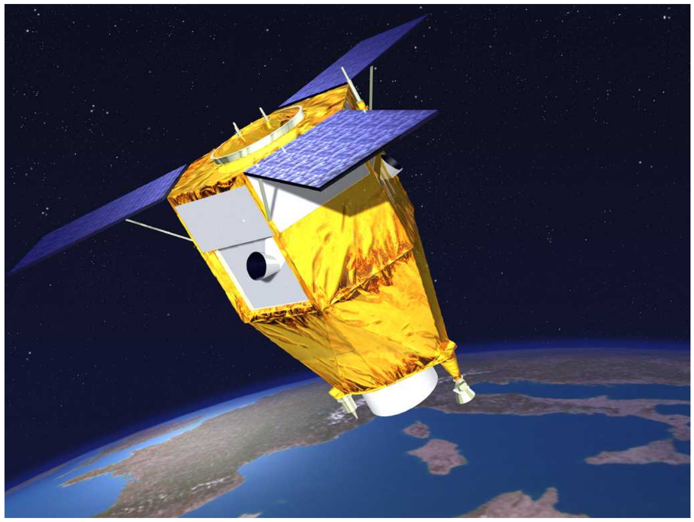
Fixed observation window
associated with each candidate observation.

Incompatibilities between observations
due to an **overlapping** between observation windows
or to an **insufficient transition time**
to allow the required mirror movement.



Agile (optical) satellites (1)

Example: the American **Ikonos** satellite, the French **Pléiades** ones.



Agile (optical) satellites (2)

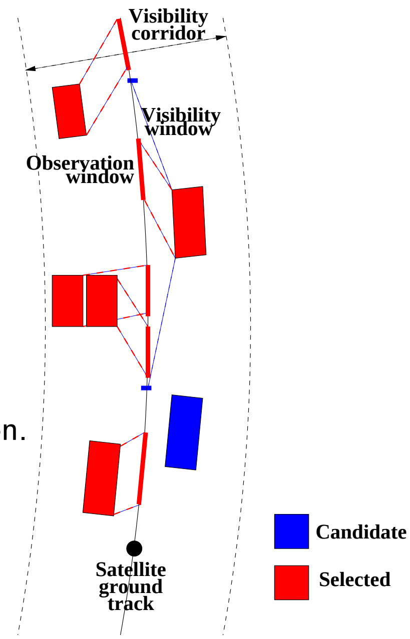
Permanent control of the satellite **attitude** along the **three axes** (roll, pitch, and yaw) via **gyroscopic actuators**.

Allows the satellite to perform **observations** and **transitions** between observations.

See **video simulation**.

Agile (optical) satellites (3)

Possible **sequence of observations**:



Visibility window
associated with each candidate observation.

Variable observation window
within this visibility observation.

More **degrees of freedom** in terms of observation.

More observation sequence **opportunities**.

Data memorization and downloading

Within the visibility window of a ground station, observation data can be **directly downloaded**.

Otherwise, they must be **memorized** in a mass memory and **downloaded afterwards**.

The available **mass memory** is **limited**.

Data downloading takes **time** and must be performed within **limited visibility windows**.

In case of an **agile satellite**, data downloading ability depends on the **satellite attitude**.

Energy production

Energy is **limited**.

It is produced by **solar panels** only during **day periods**.

In case of an **agile satellite**, it depends on the **satellite attitude**.

Possible observation failures

In case of an optical satellite, the main source of **observation failure** is the possible Earth **cloud cover**, which is **not accurately predictable**.

Summary

A **space robot**.

No obstacle to avoid. Only a **reference trajectory** to maintain.

An **attitude** to control.

No action on the world. Only **observations** to perform and observation **data** to download via equipment activations

Limited communications with the ground within visibility windows.

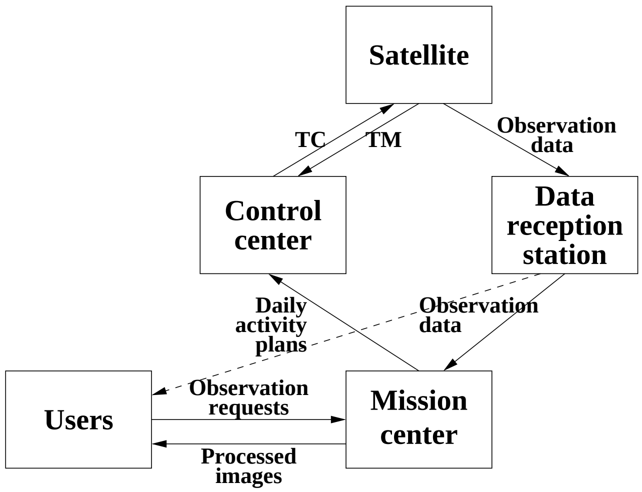
No opportunity for **repairing**. **Possible reconfigurations** using redundant equipments.

How Earth observing satellites are or could be managed

The usual approach

Daily planning of all the satellite activities, performed **on the ground**, given the current user **observation requests**.

Uploading to the satellite of a very **precise activity plan** (all the basic activities with precise activation dates), without any **on-board re-planning** opportunity.



The usual resulting problem (1)

Each day, to build for the next day an **activity plan** that is **executable** and may **satisfy as well as possible** the **user observation requests**.

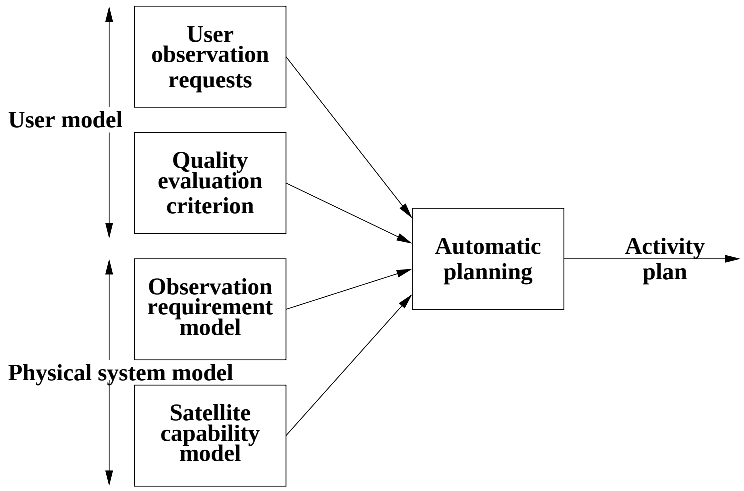
At the beginning, performed **by hand** with a large world map and small scraps of paper.

Then, the same thing with **computer support** to **visualize** observation requests and planning choices and to **check** plan executability.

Finally, **automatic planning** on the basis of:

1. the current **user observation requests**;
2. a plan **quality evaluation criterion**;
3. a model of the **observation requirements**;
4. a model of the **satellite capabilities**.

The usual resulting problem (2)



No special difficulties with the **physical system model**.

Main difficulties with the **user model**, especially with the **plan quality evaluation criterion**.

How to evaluate an activity plan (1)

1. It is usually not possible to satisfy at the same time all the user observation requests: how to **evaluate a set of selected observations** (and thus a set of not selected ones)?

2. Earth observation systems are very expensive. In Europe, they are more and more funded by several countries or several civil and military organisations: how to **evaluate a set of selected observations** from the point of view of a **fair sharing** between owner entities?

3. Some observation requests require several elementary observations (for example, a stereo observation request or a large area observation request): how to **evaluate a request partial satisfaction**?

4. There may be various ways of performing a given observation (for example, with various angular conditions), resulting in various quality levels:
how to **take into account the expected quality**?

How to evaluate an activity plan (2)

5. When an observation is planned, its success is not guaranteed, mainly because of the possible presence of clouds (with optical satellites): how to **take into account this uncertainty**?

6. New observation requests may arrive at any time, but there is no accurate model of this flow: how to **deal efficiently with the dynamic nature of the problem**?

7. Building an optimal activity plan over the next day is not the real problem. The real problem is to satisfy as well as possible the user observation requests all through the satellite life: how to **plan activities for the next day by taking into account the days after**?

The resulting problem

A **dynamic multi-criteria constrained optimization problem under uncertainty**.

Usual size: from **some tens** to **some hundreds** of candidate observations to consider.

Current and future changes in the satellite management approach

1. From the management of **one satellite** to the management of **constellations of satellites**, eventually not homogeneous (not the same instruments, not the same orbits, not the same degrees of freedom in terms of observation ...);

2. From the **centralized** management of one satellite or one constellation to the **distributed** or **coordinated** management of several space observation systems managed by independent entities;

3. From a **rigid** management (planning each day for the next day) to a **more flexible** one, for example, taking into account the arrival of **urgent requests**;

4. From a **ground** management to an **autonomous on-board** management.

Towards autonomous Earth observation satellites (1)

Main interest: to allow the satellite to **react** even **out of visibility** of a ground station (that is usually 90% of its time), in order to improve its return in terms of observation:

a. to allow it to **reconfigure** itself in case of failure and to **recover** as well as possible the curse of its mission;

b. to take into account at any time the **actual state** of the satellite and the **actual level** of its resources (energy, memory);

c. to detect the **actual cloud cover** in front of the satellite and to plan observations only in **cloud free areas**;

Towards autonomous Earth observation satellites (2)

d. to **analyze** roughly **observation data**, to **remove** too bad quality or useless images, and thus to avoid memorizing and downloading them;

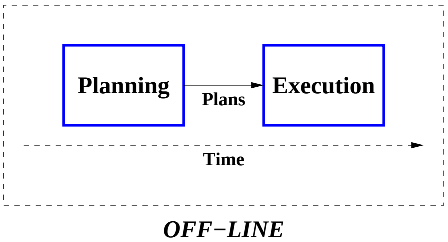
e. to **detect ground phenomena** via image on-board analysis and to **generate** on-board **new observation requests**.

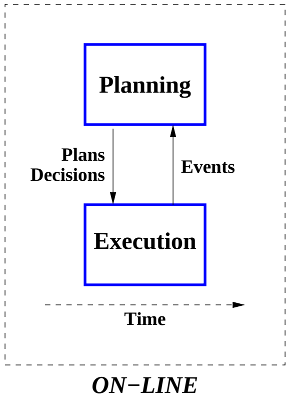
→ Towards **intelligent Earth watching and observation agents**.

EO-1: an operational example, with some of these capabilities.

The impact on planning

From regular **off-line ground** planning to **on-line on-board** planning, with **interleaved planning and execution**:





1. to take into account any **change** in the system and environment **states** and in the user **requests**;
2. to produce **good quality decisions in good time**;
3. to do that with **limited computing resources**.

Two existing approaches

1. a **plan-repair** approach, for example via **local search** in case of change, coming from the **Planning and Scheduling** community.
   See for example **(Chien & al.)**;

2. a **decision-making** approach, with **variable look-ahead**, coming from the **Real-time Search** and **Anytime Reasoning** communities.
   See for example **(Damiani & al.)**.

How the management problem can be stated

Let us consider the special case of a **non agile** satellite and the central problem of deciding upon **observations** over a given **horizon** (for example, one half revolution of the satellite), with an additive **gain** associated with each selected observation.

$\rightarrow$ A **selection** problem: among a set S of candidate observation requests, to select a subset S' that is **consistent** and **optimal** (maximum total gain).

See **(Bensana & al., Constraints, 1999)** for a precise definition of the problem.

Many ways of modelling this problem

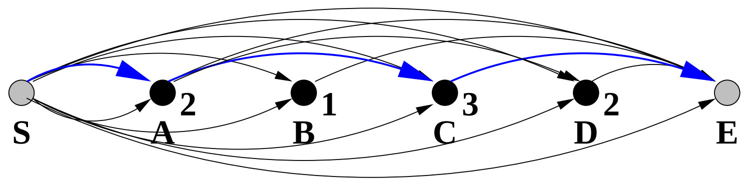
1. **Graph Theory**;
2. **Multi Knapsack Problem**;
3. **Integer Linear Programming**;
4. **Valued Constraint Satisfaction Problem**;
5. **Constraint Programming**;
6. **Sequential Decision-making**;
7. **State and Action Models**.

In fact, each community from **Computer Science**, **Operations Research**, or **Artificial Intelligence** has its own solution.

1. Graph Theory

See **(Gabrel & al.)**.

A **chaining weighted acyclic directed graph** G:
$\{i, j\} \in G$ iff observation i can be followed by observation j.



Resulting problem: to find a **longest path** from S to E.

Strengths: Very **simple formulation** and **efficient polynomial** associated **algorithms**.

Weaknesses: Does not allow **other constraints** to be taken into account. Examples: limitations in terms of memory or energy, stereo observations ...

2. Multi Knapsack Problem

See **(Vasquez & al.)**.

$$
\begin{array}{ll}
\text{Max} & \sum_{i=1}^{n} g_i \cdot x_i \\
\text{Subject to} & \sum_{i=1}^{n} m_i \cdot x_i \leq M \\
& \sum_{i=1}^{n} e_i \cdot x_i \leq E \\
& \forall \{i, j\} \in I, \quad x_i + x_j \leq 1 \\
& \forall i, \quad x_i \in \{0, 1\}
\end{array}
$$

Strengths: **simple formulation** and **efficient** optimal or approximate associated **algorithms**.

Weaknesses: Does not allow **some constraints** to be taken into account. Example: stereo observations.

3. Integer Linear Programming

See **(Gabrel & al.)**, **(Bensana & al.)**.

$$\begin{aligned}
&\text{Max} && \sum_{i=1}^{n} g_i \cdot y_i \\
&\text{Subject to} && \sum_{j=1}^{m} m_j \cdot x_j \leq M, \quad \sum_{j=1}^{m} e_j \cdot x_j \leq E \\
& && \forall \{j,k\} \in I, \quad x_j + x_k \leq 1 \\
& && \forall \{i,j\} \in M, \quad y_i = x_j \\
& && \forall \{i,j,k\} \in S, \quad y_i = x_j/2 + x_k/2 \\
& && \forall i, \quad y_i \in \{0,1\}, \quad \forall j, \quad x_j \in \{0,1\}
\end{aligned}$$

Strengths: Allows **most of the constraints** to be taken into account. Possible use of **efficient ILP tools** (example: **CPlex**).

Weaknesses: The **upper bound** provided by the **linear relaxation** is usually **poor** $\rightarrow$ **Limited cutting power** and **poor resulting efficiency**, except with sophisticated decomposition methods like **column generation**.

4. Valued Constraint Satisfaction Problem

See **(Bensana & al.)**, **(Verfaillie & al.)**.

Similar formulation, except that **non linear constraints** and **objectives** are allowed.

Strengths: Allows a more natural formulation.

Weaknesses: The computed **upper bounds** remain **poor** $\rightarrow$ **Limited cutting power** and **poor resulting efficiency**, except with sophisticated upper bound computation methods like for example **Russian Doll Search**.

5. Constraint Programming

See **(Lemaître & al.)**.

Similar formulation, except a **higher level modelling language**.

Strengths: Allows a very natural formulation. Possible use of **efficient CP tools** (example: **ILOG Solver**).

Weaknesses: Constraint propagation performs poorly $\longrightarrow$ **Limited cutting power** and **poor resulting efficiency**.

6. Sequential Decision-making

See **(Verfaillie & al.)**, **(Damiani & al.)**.

Problem seen as a **sequential decision-making** problem with **local gains** over a **finite horizon**.

$$N(i) = \emptyset \longrightarrow G^*(i) = g(i)$$
$$N(i) \neq \emptyset \longrightarrow G^*(i) = g(i) + max_{j \in N(i)} G^*(j)$$
$$G^* = G^*(0)$$

Strengths: Allows **uncertainty** about the local gains to be easily taken into account ($\longrightarrow$ **Markov Decision Process**). Efficient associated **dynamic programming** algorithms.

Weaknesses: May become quickly complex when introducing **some constraints**. Example: stereo observations. Explosion of the **state space** to consider.

7. State and Action Models

See **(Chien & al.)**, **(Frank & al.)**, **(Long & Fox)**.

Modelling in terms of possible **actions**, each with its **preconditions** and its **effects** on the **system state**. Possible use of **standard** model description languages, such as **PDDL**.

Action =

1. **name** +
2. **parameters** +
3. **duration** +
4. **condition** (at start, over all, at end) +
5. **effect** (at start, over all, at end).

Strengths: Allows a **common precise description** of all the possible actions, beyond observations. Examples: data downloading, orbital manoeuvres ...

Weaknesses: **No optimization**. **Poor efficiency** of the associated algorithms, except **plan-repair** ones performing a **local search** in the space of the complete plans.

How the management problem can be solved

Let us consider the same problem, but with an **agile** satellite.

→ A **selection** and **scheduling** problem.

See **(Cung & al., ROADEF, 2003)** for a precise definition of the problem.

To be noted:

1. as in many real problems, it is very easy to produce a **consistent** solution (to do nothing); the problem is to **improve** on it . . .

2. computing the **minimum transition time** between two observations is itself a difficult **continuous constrained optimization problem** without any good **approximation**.

Various algorithmic approaches

1. **Temporal Reasoning**;

2. **Dynamic Programming**;

3. **Tree Search**;

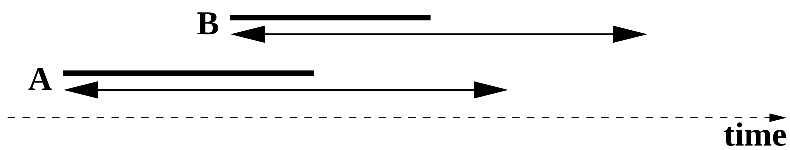
4. **Local Search**;

5. **Greedy Search**.

1. Temporal Reasoning (1)

If the **selection** and **scheduling** problem have been solved (one has decided which observations to perform and in which order to perform them), the resulting **temporal** problem (at which time to perform them) is very easy.

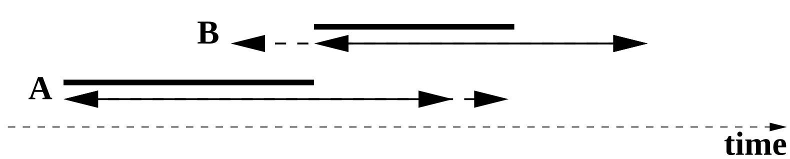
→ A **Simple Temporal Network** (STN) for which **local consistency polynomial algorithms** are **complete** and produce a **flexible** solution.



1. Temporal Reasoning (2)

If the **selection** and **scheduling** problem have been solved (one has decided which observations to perform and in which order to perform them), the resulting **temporal** problem (at which time to perform them) is very easy.

→ A **Simple Temporal Network** (STN) for which **local consistency polynomial algorithms** are **complete** and produce a **flexible** solution.



2. Dynamic Programming

If the **scheduling** problem have been solved (one has decided in which order to perform observations), the resulting **selection** problem (which observations to perform) is easy.

→ A **Dynamic Programming** algorithm based on a **discretization** of time, energy, and memory: **polynomial** and **optimal** algorithm (under the discretization restriction).

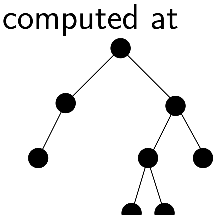
$$N(i,t,m,e) = \emptyset \rightarrow G^*(i,t,m,e) = g(i)$$
$$N(i,t,m,e) \neq \emptyset \rightarrow G^*(i,t,m,e) = g(i) + max_{j \in N(i)} G^*(j,t',m',e')$$
$$G^* = G^*(0)$$

A **natural** order: the **geographic** order (to perform observations from the north to the south).

3. Tree Search

Used in **ILP** and **CP** tools, in any **Branch and Bound** algorithm, and in many **AI Planning** algorithms.

Practicable on small and medium-size problems only if **bounds**, computed at each node, allow the tree to be **cut** very early.



Depth-first vs **Best-first** strategy:

BF. **better heuristically** informed search; potentially **exponential memory** requirements; may take time before producing a **first solution**;

DF. **worse heuristically** informed search; dependence on the **first choices**; only **polynomial memory** requirements; produces quickly a **first solution**, but may take time before improving on it; not very good **anytime** behavior.

4. Local Search

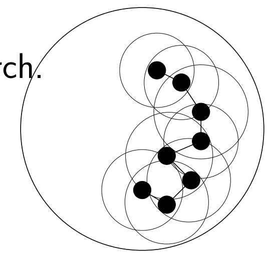
Many forms: **Tabu search**, **Simulated annealing**, **Genetic algorithms** . . .

No standard. Many **parameters to tune** before getting an efficient algorithm. Importance of the **programmer's experience** and **skills** .

Some difficulty dealing conjointly with the **constraints** and the **criterion**.

Main parameters:

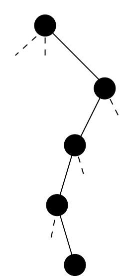
1. the mechanism used to generate a **first solution**;
2. the **neighborhood relation**;
3. the mechanism used to **explore** the neighborhood and to **choose** a new solution in it;
4. the criterion used to **stop** and eventually **restart** the search.



Generally good **anytime** behavior,
especially with **Tabu search** and **Simulated annealing**.

5. Greedy Search

The **last solution** when everything else failed,
or the first solution if you are lazy or in a hurry.



Importance of the **order** in which successive choices are made.
Time may be a good order.

An interesting **variant**: **repeated greedy search** with **heuristically biased stochastic choices**;
used in the domain of **telescope** management
(see Bresina, AAAI, 1996).

Results from experiments and practice

Results from experiments carried out at ONERA (1)

See **(Lemaître, Verfaillie)**.

Agile satellite. **Comparisons** between:

1. **GA**: a **Greedy** algorithm, making greedy decisions according to the **temporal order**;
2. **DPA**: a **Dynamic Programming** algorithm, using a **fixed observation sequencing** and a **time discretization**;
3. **CPA**: a **Constraint Programming** algorithm, using the generic **OPL Studio** tool, that is a combination of **tree search** and **constraint propagation**;
4. **LSA**: a dedicated **Local Search** algorithm, locally modifying **observation selection** and **sequencing**.

Results from experiments carried out at ONERA (2)

Linear optimization criterion. **Stereoscopic** constraints ignored.

instance id	# strips	GA	DPA	CPA	LSA av. (max.)
2:13_111	106	532	**603**	442	574 (587)
2:15_170	295	707	**843**	527	723 (779)
2:26_96	483	831	**1022**	782	826 (877)
2:27_22	534	895	**1028**	777	800 (861)
3:25_22	342	436	**482**	253	345 (375)
4:17_186	147	188	**204**	177	192 (196)

1. **GA**: **Greedy** algorithm;
2. **DPA**: **Dynamic Programming** algorithm;
3. **CPA**: **Constraint Programming** algorithm;
4. **LSA**: **Local Search** algorithm.

GA and **DPA**: very fast.

Results from experiments carried out at ONERA (3)

Non linear optimization criterion. **Stereoscopic** constraints taken into account.

instance id	# strips	CPA	LSA av. (max.)
2:13_111	106	241	**414** (490)
2:15_170	295	350	**446** (490)
2:26_96	483	439	**516** (592)
2:27_22	534	410	**455** (561)
3:25_22	342	149	**255** (298)
4:17_186	147	125	**145** (156)

1. **CPA**: **Constraint Programming** algorithm;
2. **LSA**: **Local Search** algorithm.

Results from the ROADEF Challenge (1)

See **(Verfaillie & al.)**, **(Cung & al.)**.

10 unknown difficult instances (some hundreds of observations).

5 minutes to solve each instance.

10 executions per instance for non deterministic algorithms.

Independent comparison on the **same machine**.

The **winners**: **Simulated Annealing** or **Tabu Search** algorithms, highly **tuned** to deal with the agile Earth observation management problem and carefully **implemented** to allow **quick** and **relevant local changes**.

Results from the ROADEF Challenge (2)

No use of **dynamic programming** algorithms.

No use of generic **ILP** or **CP** tools, like **Ilog Solver** or **CPlex**.

Clear failure of the algorithms based on **ILP** and **CP** formulations, even with a highly tuned **control** of the **tree search**.

Lower and upper bounds

See **(Vasquez, Hao)**, **(Bianchessi & al.)**.

Maximization problem:

- optimum **lower bounds** provided by **local search** algorithms (the value of a solution is always an optimum lower bound) $\longrightarrow$ typically **fast** algorithms;
- optimum **upper bounds** provided by **complete search** algorithms running on problem **relaxations** (for example problem decomposition; the optimum of a relaxation is always an optimum upper bound) $\longrightarrow$ typically **slow** algorithms.

Results: typically 0, 1, or 2% between lower and upper bounds, using **sophisticated** lower and upper bounding algorithms.

Lesson: sophisticated local search algorithms allow **near optimal** solutions to be produced.

A glance at the near and far future

The future

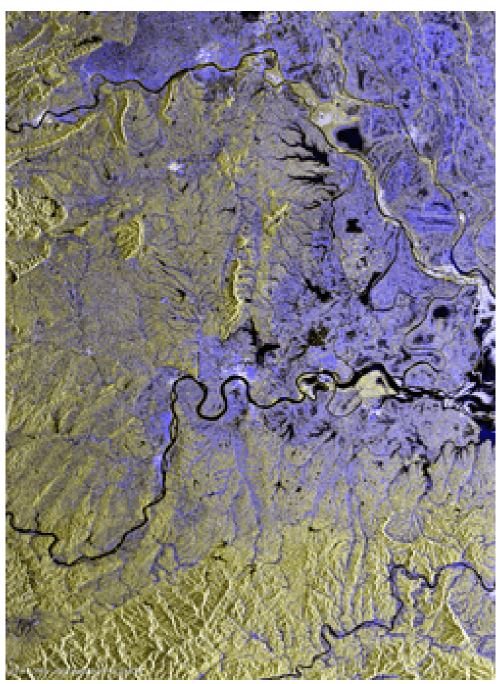
A **network** of **interconnected intelligent** Earth sensors, able to **detect** and to **track** Earth phenomena, like:

- **forest fires**;
- **volcanic eruptions**;
- **floods**;
- **earthquakes**;
- **tidal waves**;
- **iceberg formations and movements**;
- **pollutions** ...

Forest fires in Amazonia

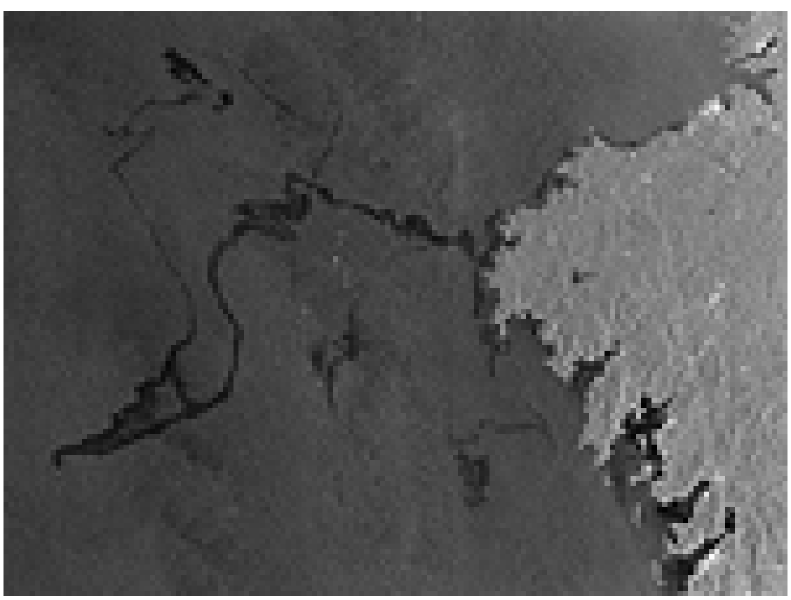
Eruption of Etna in Sicily

Floods in China



Icebergs in the Arctic Ocean

Wreck of a tanker in front of Galicia (Spain)



Challenges

1. a **global detection** and **alarm** system;

2. an efficient handling of **specific user requests**,
   from request expression to data delivery;

3. an **optimization** of the **use** of the global system;

4. a **cooperation** between various Earth sensing systems and a stronger **reactivity** of each system;

5. **sensing**, **data analysis**, and **autonomous cooperative decision-making** capabilities on-board each satellite;

6. **formation flying** satellites to perform for example **interferometric observation** missions.

$\longrightarrow$ A **network** of **autonomous cooperative** observation **agents**.

Commented Bibliography on Planning for Earth Watching and Observing Satellites and Constellations

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Abstract

This document is a commented bibliography around the problem of planning activities for Earth watching and observing satellites and constellations. It is associated with a tutorial given on this topic at ICAPS 2006 (International Conference on Automated Planning and Scheduling), in Cumbria, English Lake District, UK.

Sometimes, two references point to very similar papers published in different forums. In such a case, we deliberately we provide the reader with both references as two paths to the same content.

We are the only responsible for the short commentaries that are associated with each reference. Any misunderstanding or omission may be pointed out to us.

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