International Workshop on Planning and Scheduling for Space

Planning of satellite images applied to early warning hydrological models

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Motivation

- In emergency management time plays a major role;
- Earth Observation Satellite systems response time is a key variable;
- Even for most reactive systems we frequently loose the opportunity of having the first images of an emergency because they are requested once the event has already started;
- An on board detection and re-planning approach like the one used on EO-1 can cut the effective response time greatly, but cannot completely overcome this problem;
- Whenever possible, forecasting seems to be the only answer to this;
- In the particular case of flooding, it is possible to use an operational medium fidelity physics model to forecast the risk of flooding events and select in advance which are the most convenient acquisitions to request;
- Even gathering images before the event has started and capture its important transitory dynamics becomes possible.

Satellites and sensors used

Using RADARSAT-2 and ALOS satellites in the model allowed us to have both optical and radar images with different resolutions, coverages and acquisitions modes, and at the same to keep the problem simple with only two satellites.

RADARSAT-2

Its principal instrument is a SAR with quadri-polarization, very useful for flood events monitoring, designed with 10 modes of acquisition and offering a range of incidence angles allowing to choose the beam position with each mode. Each acquisition mode has a particular area coverage and spatial resolutions (from its highest resolution of 1m to 100m.)

ALOS

It has three instruments: L-band SAR, a panchromatic camera and a visible and near infrared radiometer.

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Hydrological Model

The Saint Venant Equations - The kinematic wave

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$

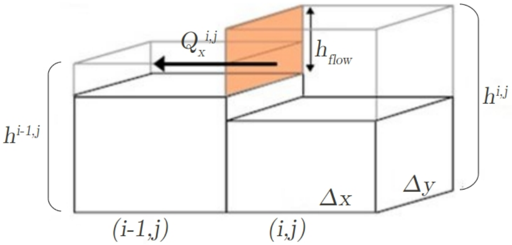
$$S_0 - \frac{n^2 Q^2 P^{4/3}}{A^{10/3}} = 0$$

Where Q is the flow in the channel, A is the cross sectional area of flow, q is the water input from others sources, S_0 slope of the river bed, n is the Gauckler-Manning coefficient and P is wetted perimeter.

Hydrological Model

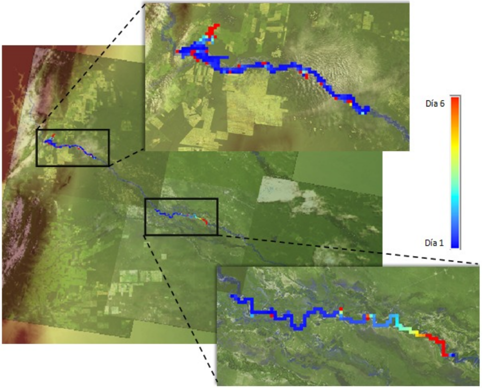
$$\frac{dh^{i,j}}{dt} = \frac{Q_x^{i-1,j} - Q_x^{i,j} + Q_y^{i,j-1} - Q_y^{i,j}}{\Delta x \Delta y}$$

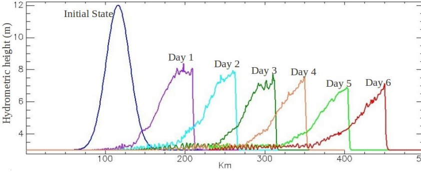
$$Q_{x,y}^{i,j} = \frac{h_{flow}^{5/3}}{n} \frac{(h^{i-1,j} - h^{i,j})^{1/2}}{\Delta x} \Delta y$$

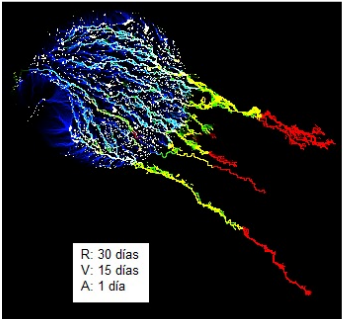


Where $h^{i,j}$ is the height of free water surface at node (i,j), t is time, Δx and Δy are the grid cell dimensions, n is Manning's roughness coefficient of foodplain, Q_x and Q_y describe the volumetric flow rates between adjacent floodplain and h_{flow} represents the depth through which water can flow between two cells.

Hydrological model forecasting results on foodplain







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EOS modes and user preferences

For each EOS we define the set $M = \{1, ..., k\}$ that encodes all its possible acquisition modes and a function *mode preference* for each request:

$$mp_r : M \longrightarrow MP$$

that associates to each element in M a value in the $MP = \{1, ..., n\}$ *mode preference* set used to define the user preference for each particular mode, (1 is its maximum preference and n its minimum).

Users requests

An *Acquisition Request* $r \in R$

- a target area definition a_r
- an acquisition mode preference definition mp_r stating what modes are more useful for the user
- the priority pr_r that defines the importance of the request for the user
- a validity period v_r within which the acquisition is useful for the user

where: R is the set of all users requests.

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Connecting the hydrological & planning models

Hydrological risk forecast ⟷ target area priority/mode preference

- In the hydrological model, the region of interest is divided in small cells that follows the river course and its neighborhood, conforming the set of potential acquisition target areas useful for the application;
- The hydrological model forecast (e.g. a downstream wavefront flood and overflow zones) is used to generate a flood risk prediction value for each one of this target areas per day;
- This flood prediction risk is used to assign greater priorities to the areas with higher flood risk, i.e. for any acquisition request r, the priority pr_r is determined by the output of the hydrological model forecasting for the period
- Also it is used to determine criteria about which acquisition mode use, for example: we request low spatial resolution if the flooded area is narrow.

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Candidate Images

Using SaVoir and the set of all users requests R, by identifying all the possible images that at least partially cover the target areas defined in the users requests we generate an initial set of candidate images.

- I is the set of all *candidate images* within the planning time horizon corresponding to day D.

Given a user acquisition request $r \in R$, we denote by I_r the subset of I with all possible candidate images that are present in I (notice: $I = \bigcup_{r \in R} I_r$).

Image acquisition request planning problem overview

a. Initial State: no image is selected or discarded;
b. Actions:to select or discard candidate images;
c. Goal State: bounded (on the number of selected images) or unbounded;
d. An WA* algorithm searches a feasible solution S that minimize the objective function $F(S)$;
e. The objective function $F(S)$ has four terms that consider the request area coverage, the request priority (weighted in correspondence with the request area coverage), the request mode adequacy and the swath usage.

Note 1: Consistency with the temporal constrains determines when a set of candidate images is a feasible solution.

Temporal constraints

Useful temporal constraints over acquisitions usually can be divided in:

a. constraints over any number of acquisitions but over a period of time (e.g. per day or per orbit);
b. constraints over pairs of acquisitions (usually contiguous);
c. constraints over a single acquisition.

Temporal constraints over pairs of candidate images

Feasible Solution

Given a subset of I denoted by S, we said that S is a *feasible solution* that satisfy all temporal constraints when for any pair $(i, j) \in S \times S$ we have that $et_i + tt_{ij} < st_j$ or $et_j + tt_{ji} < st_i$.

where: tt_{ij} is the minimum transition time the satellite needed between the end of an acquisition i and the start of acquisition j.

Candidate, Selected and Discarded Images

In addition to the set of all *candidate images* I, we have the following two important sets:

Selected images

SI is the subset of I with all *selected images* such that SI is a feasible solution.

Discarded images

DI is the subset of I with all *discarded images* those images that if added to S make the set not a feasible solution.

Objective Function

$$F(S) = \alpha f_{ca}(S) + \beta f_{pa}(S) + \delta f_{ma}(S) + \sigma f_{us}(S)$$

With:

$$\mathrm{f}_{ca} = \sum_{i \in S} 1 - ca_i \qquad f_{pa} = \sum_{i \in S} \frac{pr_i * (1 - ca_i + 1)}{2}$$

$$\mathrm{f}_{ma} = \sum_{i \in S} \frac{ma_i}{k} \qquad f_{us} = \sum_{i \in S} 1 - us_i$$

- f_{ca} measures the quality of the solution regarding total covered area.
- f_{pa} measures the quality of the solution regarding areas with greater priority.
- f_{ma} measures the quality of the solution regarding the acquisition mode adequacy. Where $k = |MP|$ is the cardinality of MP, the value that correspond to the lowest preference.
- f_{us} measures the quality of the solution regarding swath percentage over the area of interest.

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Implementation

Planner Tool

- Domain Independent Language
- Metric-ff planner (support metrics)
- WA* algorithm (*Best-First Search*)
  $f(n) = wg * F(S) + wh * h(n)$

Planning domain definition

The domain and planning problem were specified in PDDL v2.1. Four objects were defined:

a. image: representing each candidate image;

b. mode: representing the various modes in M;

c. area: representing an acquisition request target area;

d. D: representing current day.

Actions

We use seven actions to select (3) or discard (4) candidates images.

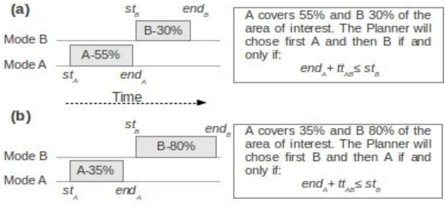

Figure: States where is possible to acquire both image

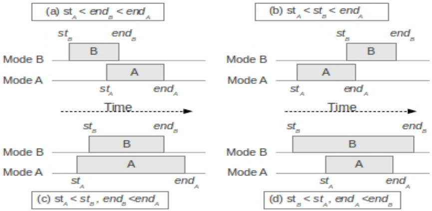

Figure: States where is not possible to acquire both image

Initial and Goal states

Initial state

$$SI \cup DI = \emptyset$$

Goal

- *bounded goal*
  $|SI| = m$,where m is the maximum number of images
- *unbounded goal*
  All the images in I are selected or discarded (i.e. $SI \cup DI = I$).

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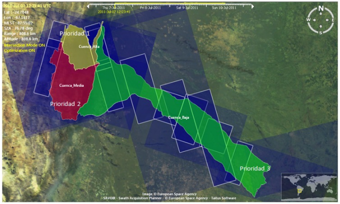
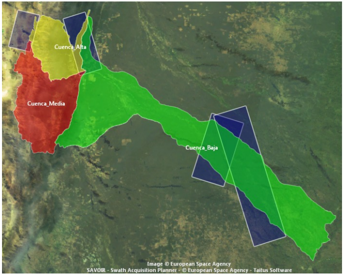
Tests and results

Scheduled images	Selected images	Visited nodes	Time	Metric	Scenarios
8	3	48	0.47"	f_{ca}	A
8	2	52	0.62"	f_{ma}	A
8	3	48	0.47"	$f_{ca}+f_{ma}$	A
8	3	48	0.31"	f_{us}	A
12	4	2976	2.96"	f_{pa}	B
18	9	867	22.15"	f_{ca}	C
18	6	95	19.19"	f_{ca}	D





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Architecture of the integrated system

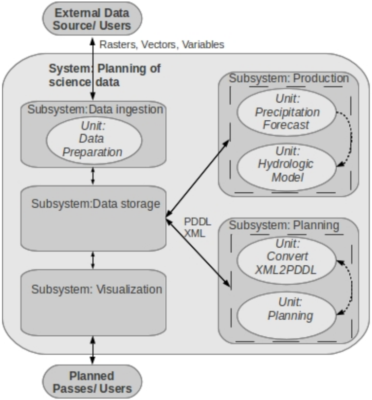

Figure: Architecture of integrated system

- Data ingestion subsystem (SI)
- Data storage subsystem (SA)
- Production subsystem (SP)
- Planning Subsystem (SPLA)
- Display Subsystem (SVI)

One integrated scenario

The hydrological model was ran on Bermejo River basin (north of Argentina). For a time window equal to seven days two overflow regions were forecasted for the model. Because the overflow areas are narrow regions, it was worked with *Ultrafine* (3m spatial resolutions) and *Fine* (8m spatial resolutions) modes of SAR sensor onboard Radarsat satellite

Figure: Gantt Chart: potential acquisitions on critical regions (13 images)

One integrated scenario

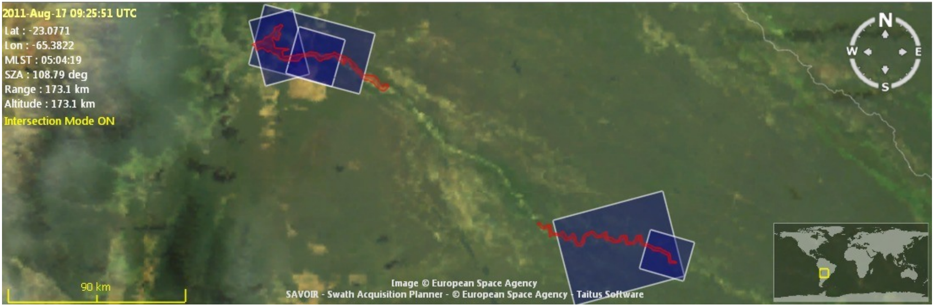

Figure: Map of the selected images on the critical regions

The planner found a solution in 40 seconds and went through 30782 nodes and the plan was evaluated according the total of covered area by each image and its acquisition mode.

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Future work

- To improve the image acquisition planning model, tools and algorithms used in several aspects like:
  a. To use different modeling and algorithms for the optimization problem, including the use of planing and scheduling tools that allows a better temporal representation;
  b. To consider constraints on the number of acquisitions for a given period of time and constraints over single acquisitions and other constraints that reflect better ground, satellite and communications limitations.
  c. To automatically cut all parts of a user request target area when acquired in order to pass to the next planning cycle only the uncovered parts of that area;
- To put in place various operational hydrological applications of emergency management for various flood basins over Argentina to be used in the context of CONAE's SAOCOM mission;
- To apply this approach to other applications like wild fire management, or malaria and dengue fever control.

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Conclusions

- The simplified wave hydrological model implemented predicts the affected areas and provides information about the movement of the flood wavefront that progresses downstream;
- The model showed good numerical stability taking into account hydraulic principles such as mass conservation and flow connectivity;
- The image acquisition planning system we developed based on the planning domain and problem models described above shows that it is possible with available tools to use the hydrological model flood risk predictions to prioritize the acquisition image planning problem;
- The approach developed shows that when reasonable forecasting is possible, we can overcome the EOS system reaction time constrains and start acquiring useful data from even before the start of the flood event.

Thanks for your attention!

Questions?