New modules for satellite surveying planning in GRASS

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Abstract

Satellite surveying techniques are gaining always more relevance for several application fields such as surveying, environmental monitoring and navigation. The main benefit of these techniques is the possibility of establishing the position of points even when they are not visible to each other, but at least four satellites must be visible at the same time. In practical surveying natural (mountains, etc.) or manmade (buildings, etc.) obstacles often hide satellites signal to the receiver.
It is therefore important to know in advance where signal will be concealed by obstacles and when the signals from a sufficient number of satellites will be available for the survey.
Three new modules for the open source GRASS GIS has been created which automatically determine obstacles to the satellites signal to detect the satellites coverage and the PDOP value, on a time window, for a given area, using as input the digital terrain model (DTM) and the satellites almanac.
The new module r.obstruction reads the DTM and creates an ASCII file containing a polar representation of the obstructions with one degree resolution.
The new module r.planning.static uses the DTM and the obstructions file to generate four different raster maps: two raster maps representing the number of visible satellites at starting time and the minimum number of visible satellites over the chosen time span and two raster maps showing the PDOP values at starting time and the maximum PDOP values over the chosen time span.
The r.planning.static module can also be used for single point planning using a map as reference for choosing the points on the graphical display with the mouse.
The third module r.planning.cinematic can be used for the planning along a trajectory. Such trajectories, in vector format, can be over the terrain surface, at constant height or fully three dimensional. Starting time and mean speed are used to estimate the time for each node. The output is given as GRASS site data, each point having four attributes: height, number of visible satellites, PDOP and time from previous point.
Satellites' positions are evaluate from the almanac as downloaded directly from the receiver or as obtained through the Internet from IGS.
Several applications of the new modules have been carried out, among these the realistic planning of geodetic surveys and the feasibility study of the satellite monitoring of wild life, in particular for the possibility of tracking the wild bears in the Alps.
The availability of the new modules in GRASS carries two main advantages: an environment to manage the geo-referenced data constituting the input and the output of the procedure and the possibility of integrating these techniques within the wide range of GIS procedures.

1. Introduction

Satellite surveying is nowadays widely used and still gaining new popularity for traditional topographic applications and for completely new applications such as environmental monitoring, meteorology and navigation.
This technique offers several advantages with respect to traditional ones, for example the point inter-visibility is not needed, but the requirement of having at least 4 (or 3 if the height coordinate is not required) visible satellites must be fulfilled. Moreover, the accurate forecast of the satellites' visibility plays a major role on the assessment of the final precision and reliability of this kind of surveys.
While satellite configurations are usually designed to provide an adequate coverage of the whole earth surface, providing a theorical availability of at least 4 satellites for every point of the earth surface, natural obstacles and artifacts can meaningfully reduce the system usability by obscuring the satellites' signals to the receiver.
This problem becomes relevant in mountainous areas, where the obstacles are natural, and in urban areas, where artifacts can hide a significant part of the sky.
It is therefore important the possibility of performing an accurate planning of a satellite survey. Moreover, for this planning, forecasting the satellites' availability using predicted orbits and obstacles knowledge for the survey area, accurate information about the obstacle must be available.
This is usually accomplished by performing a polar obstruction diagram in situ. However, this procedure is usually expensive and time consuming, especially when a large number of points must be determined, and it becomes impossible for cinematic surveys.
The problems above can be bypassed by using a numeric representation of the survey area and by performing an obstacle search therein. This idea can be brought a step further by numerically performing also the comparison between obstacles and satellites' positions, i.e. determining satellites' visibility automatically.
The "natural" environment for setting up the procedure above is a GIS, where a surface description and related manipulating functions are available, while specific procedures must be added for satellite positions estimation and for the final visibility estimation.

2. GPS survey planning

One of the main advantages of the satellite surveying technique is that the points of the network do not need to be mutually visible; however, at least 4 satellites must be available for the determination of the four unknowns (3 coordinates and the time skew between the satellites' time and the receiver's time).
For the determination of the satellites' visibility two kind of information must be merged: satellites' positions and obstacles' position and shape.
The satellites configuration is routinely predicted by the Ground Control Segment, uploaded to the satellites and sent to the final users. Two kind of products suitable for the planning are available:

- predicted (broadcast) ephemeredes: they provide a good precision, they are in fact usually used for the final position determination in a satellite survey, but remain valid for a short period of time (about 24 hours).
- almanac: this data, which is sent along the navigation signal, provides information about the future ephemeredes, with lower precision with respect to predicted ephemeredes, and about the satellites' status.. However, this information remains valid for a long period of time (about a month) and the precision is sufficient for a correct survey planning.

The latter ephemeredes forecast is currently used for satellite survey planning by commercial software; the new GRASS modules presented here can use both the type of prediction.
The precision of the satellites' positions given by the almanac data can be estimated in the order of some kilometers, while broadcast ephemeredes provide a precision of about ten meters.
In the worst case, a precision of about 5 kilometers for the satellites' positions can be assumed: as a consequence a one degree approximation for the satellites' elevations above the horizon must be taken into account (D'Inca', 2001) for creating the final visibility map.
This precision corresponds to an uncertainty on the ground of the satellite's "shadow" that depends on the height and angle above the horizon (or distance) of the obstacle, for example:

$$\left.\begin{array}{r}\alpha = 20^\circ \\ \Delta H = 2000m\end{array}\right\rangle \Rightarrow \Delta \cong 300\delta^S{}_{[\text{deg}]} \Rightarrow \Delta \cong 5m$$

$$\left.\begin{array}{r}\alpha = 10^\circ \\ \Delta H = 2000m\end{array}\right\rangle \Rightarrow \Delta \cong 1200\delta^S{}_{[\text{deg}]} \Rightarrow \Delta \cong 20m$$

$$\left.\begin{array}{r}\alpha = 90^\circ \\ \Delta H = 2000m\end{array}\right\rangle \Rightarrow \Delta \cong 35\delta^S{}_{[\text{deg}]} \Rightarrow \Delta \cong 60cm$$

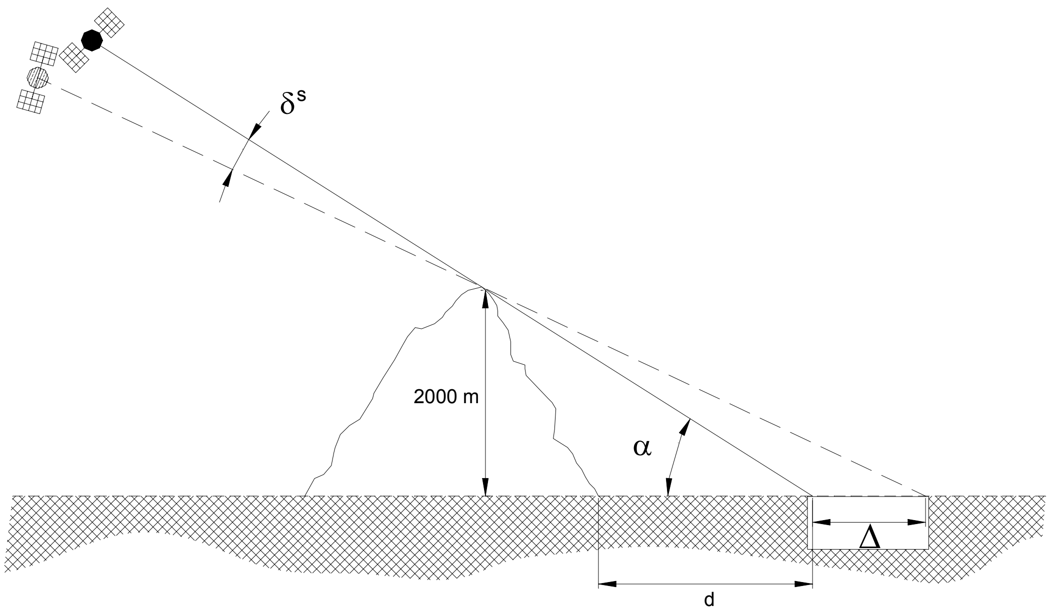


Figure 1 – Relationship between satellite's position and obstacle.

Satellites' motion imposes a temporal limit to the validity of a planning since the constellation configuration changes continuously. Simple calculations on satellites' height and speed indicate that the satellites' positions uncertainty is of the order of magnitude of one degree along its orbit (the same of that due to almanac approximations) for a time interval of 2 seconds (D'Inca', 2001). Such a short time is not feasible for an actual planning, therefore a compromise between spatial and temporal resolution must be made. For example a period of time of 5 minutes yields an uncertainty on satellite's position δ^s of 2.5 degrees which corresponds to a "shadow" limit uncertainty Δ of 750 m for an obstacle elevation α of 20 degrees.
The evaluation of some Dilution Of Precision indexes is a common practice in satellite survey planning, summarizing in this way the suitability of a satellite constellation for the survey. This is

done by simple algebraic calculations on the design matrix of the spatial configuration of the visible satellites.

3. Data sources

Commercial software for satellite survey planning compares satellite's position with an handmade polar diagram of the site obstacles. The only required external data are given by the satellite almanac, which is usually downloaded directly by the receiver along with the navigational message and then transferred to the planning software.
Since the new approach proposed here uses a numerical description of the survey area to automatically depict the obstacles to the receiver-satellite intervisibility, additional data are required. Satellites' position can be determined by the usual almanac data or by the broadcast ephemeredes. If the almanac is used, it must be converted into an ASCII format, such as that exported by the "Geotracer" software by Geotronics (Sweden):

1	2	3	4	5	6	PRN
0000	0000	0000	0000	0000	0000	Stato
0.004170	-0.013738	0.001984	0.004711	0.001094	0.006560	e
5153.6	5153.6	5153.6	5153.7	5153.6	5153.7	$a^{1/2}$ (m)
-42.690	73.115	135.034	-163.075	74.103	137.110	Ω_0 (°)
-94.518	-131.567	136.187	-46.090	-20.261	-147.837	ω (°)
178.985	-76.024	84.392	57.786	69.101	103.846	M_0 (°)
503808	503808	503808	503808	503808	503808	t_a (s)
0.7519	-0.1995	0.4377	1.9683	-0.0350	0.8532	δi
-0.0004525	-0.0004623	-0.0004643	-0.0004558	-0.0004623	.000461	$d\Omega/dt$ (ns)
43869.0	-472068.8	114440.9	20027.2	143051.1	0.0	a_0 (ns)
0.00	-0.00	0.00	0.00	0.00	0.00	a_1 (ns)
951	951	951	951	951	951	GPS week

Explanations about the parameters above can be found in (D'Inca', 2001).
While broadcast ephemeredes are routinely downloaded from the receivers only for the satellites actually tracked, the ephemeredes of all the satellites must be available. Comprehensive broadcast ephemeredes can be found in internet in the standard RINEX format, for example from the IGS ftp site ftp://igs.ensg.ign.fr/pub/igs/data, where this kind of data is archived starting from 1996:

```
     2              NAVIGATION DATA                         RINEX VERSION / TYPE
CCRINEXN V1.5.9 UX  CDDIS               02-APR-00 07:11     PGM / RUN BY / DATE
IGS BROADCAST EPHEMERIS FILE                                COMMENT
    0.4191D-07  0.1490D-07 -0.2384D-06 -0.5961D-07          ION ALPHA
    0.1495D+06  0.0000D+00 -0.3932D+06  0.3932D+06          ION BETA
    0.177635683940D-14 0.931322574616D-09   503808     1107 DELTA-UTC: A0,A1,T,W
    13                                                      LEAP SECONDS
                                                            END OF HEADER
 1 01  3 29  0  0  0.0 0.170486513525D-03 0.170530256582D-11 0.000000000000D+00
    0.233000000000D+03 0.235625000000D+02 0.463590738987D-08-0.152674640197D+01
    0.112131237984D-05 0.521562073845D-02 0.670924782753D-05 0.515358573532D+04
    0.345600000000D+06 0.558793544769D-08-0.144479337568D+01 0.987201929092D-07
    0.963384700085D+00 0.250843750000D+03-0.170204798513D+01-0.811605235187D-08
    0.234295473633D-09 0.100000000000D+01 0.110700000000D+04 0.000000000000D+00
    0.340000000000D+01 0.000000000000D+00-0.325962901115D-08 0.233000000000D+03
    0.338406000000D+06 0.000000000000D+00 0.000000000000D+00 0.000000000000D+00
```

Again, explanations about the parameters above can be found in (D'Inca', 2001).
Numeric representation of the survey area is given by a Digital Terrain Model (DTM), a raster data file where each cell is assigned an height. GISs, and GRASS used for this work, provide routines for creating and manipulating DTMs.
The ground resolution of the DTM obviously influences the accuracy of the obstacles' description and the resolution of the final visibility map. The accuracy of obstacles' description must match the accuracy of the other parameters, a 40 m resolution is probably a good choice in most of the situations. In fact, a 40 m resolution DTM usually has an height precision around 10 m, which corresponds to a 30 m uncertainty for satellites 20 degrees above the horizon.
A further approximation comes from the fact that, while satellites' positions are given in the WGS84 reference system (usually over UTM projection system), the DTM heights are given with respect to the geoid, as defined by the national or regional reference system. However, the difference between ellipsoidal and orthometric height (geoid undulation) can be neglected here since it induces lower approximations with respect to all the other ones.

4. Static and cinematic planning

While commercial software performs only planning for static surveys one point at a time, it would be useful to carry out planning for entire areas, achieving a map of the satellite visibility and related parameters. Moreover, the use of satellite techniques for cinematic surveys is rapidly becoming more relevant, thus the availability of a procedure for planning such measurements is now very valuable.
Regardless the type of planning (static or cinematic) the procedure can be splitted in two steps:

1. a polar map of the elevations of the obstacles above the horizon is created from the DTM;
2. the satellites' positions are computed and their visibility is evaluated by comparing satellites' and obstacles' elevations.

The advantage of such approach is that DTM, and therefore the obstacles' elevations, does not change in time. For this reason the first step of the procedure, which imply a high computational load, can be performed only once.
The second step involves issues rapidly changing in time as satellites' positions are. Therefore it must be performed for each planning time or more than once per each planning if its time span is longer than that acceptable for the approximations due to the satellites' motion (see paragraph 2).
The evaluation of the elevation of each satellite is the heavier part of the second step of the procedure, for this reason when the planning is performed for a whole area, creating a satellite visibility map, the elevation is computed only once for the entire map. The approximation due to this procedure is acceptable as long as all the points lie within a radius of 6 km.

5. New GRASS modules

Three new GRASS modules have been created to carry out a satellite survey planning performing the two steps described in the previous paragraph.
In particular one module (r.obstruction) creates a polar obstructions' map, while two modules use this map to perform a static (r.planning.static) or a cinematic (r.planning.cinematic) planning. Both this last two modules evaluate the constellation's PDOP (Position Dilution Of Precision).

The **r.obstruction** GRASS module creates a file with the elevation of the obstacles above the horizon starting from a DTM raster map. It is possible to establish a cut-off value which provides a minimum value for the elevation regardless to the real obstacles. Moreover, it is possible to set an height value so that all the DTM heights below are set to this value: this can be useful for planning a plane flight to a certain height.
The complete synopsis is the following:

```
r.obstruction input=name [cut=value] [height=value]

Parametri:
   input   DTM aster map name
     cut   cut-off angle : (range 10-90)
           options: 10-90
           default: 10
height     costant height for the DTM minimum
           default: 0
```

This modules outputs the obstructions' elevation in the following ASCII format:

- an header reporting the name of the input DTM file, the numbers of its columns and rows and its boundaries;
- a line for each pixel of the DTM reporting a total of 360 values for the obstacle elevation, one value for each degree, clockwise from the north direction. The first row does not contains real values but the indication of the degree (each ten of them) to make the file more readable from a human operator.

```
File di input:59120verif
Cols= 115
Rows= 94
North= 5105040
South= 5101280
East= 1652680
West= 1648080

                            10                            20              ……………360
10 10 10 10 10 14 14 10 10 10 10 10 10 10 10 10 10 10 10 10 ..
10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 ..
10 10 10 10 10 10 10 12 12 12 12 12 15 15 17 17 17 17 22 22 ..
29 29 29 37 37 42 42 42 42 50 60 68 68 68 68 68 68 68 68 68 ..
...
```

This file can be very large and long to create, but it is generated only once and stored for future use.

The **r.planning.static** module performs a static planning using the obstruction file as input. Input data carry information about surface geometry, satellites' positions and time of planning.
The obstacles description is given by the obstruction file, however the original DTM raster file is still required and it is used to calculate the position of the baricentric point and the mean height. For this last calculation the name of a reference ellipsoid can be given, the Hayford ellipsoid is the default one.
Satellites' positions can be given by the broadcast ephemeredes or by an ASCII almanac. This choice is controlled by a proper flag.
The planning time is given through two parameters: starting time (date and time) and duration. The latter allows the evaluation of the worst scenario for a static planning with a long duration: along the situation (satellites' visibility and PDOP) at the starting time, the worst values of the parameters over the time span are provided. To take into account the satellites' constellation evolution during this time, satellites' visibility and PDOP are calculated every 5 minutes, according to the approximations discussion of paragraph 2.

The complete synopsis is the following:

```
r.planning.static [-pc] raster=name almanac=name obstructions=name
```

```
                date_time=name [ellipsoid=name][duration=value]

Flags:
  -p   (y)planning for one pixel   (n)planning DTM
  -c   (y)=almanac file from the net  (n)=rinex format almanac

Parameters:
        raster   raster file to be processed
       almanac    name of GPS file almanac
  obstructions   file obstructions
     date_time   Date and time of planning (ex. 3 Jan 1984 16:33:45)
     ellipsoid   ellipsoid name
                 default: hayford
      duration   planning duration (hours)
                 options: 1-24
                 default: 1
```

With this module it is possible to perform a planning for a single pixel of the DTM (and obstruction map) or for the whole elevation map.
In the first case the point position must be provided either by entering its east and north coordinates or by choosing a point with the mouse on a graphical terminal (figure 2).

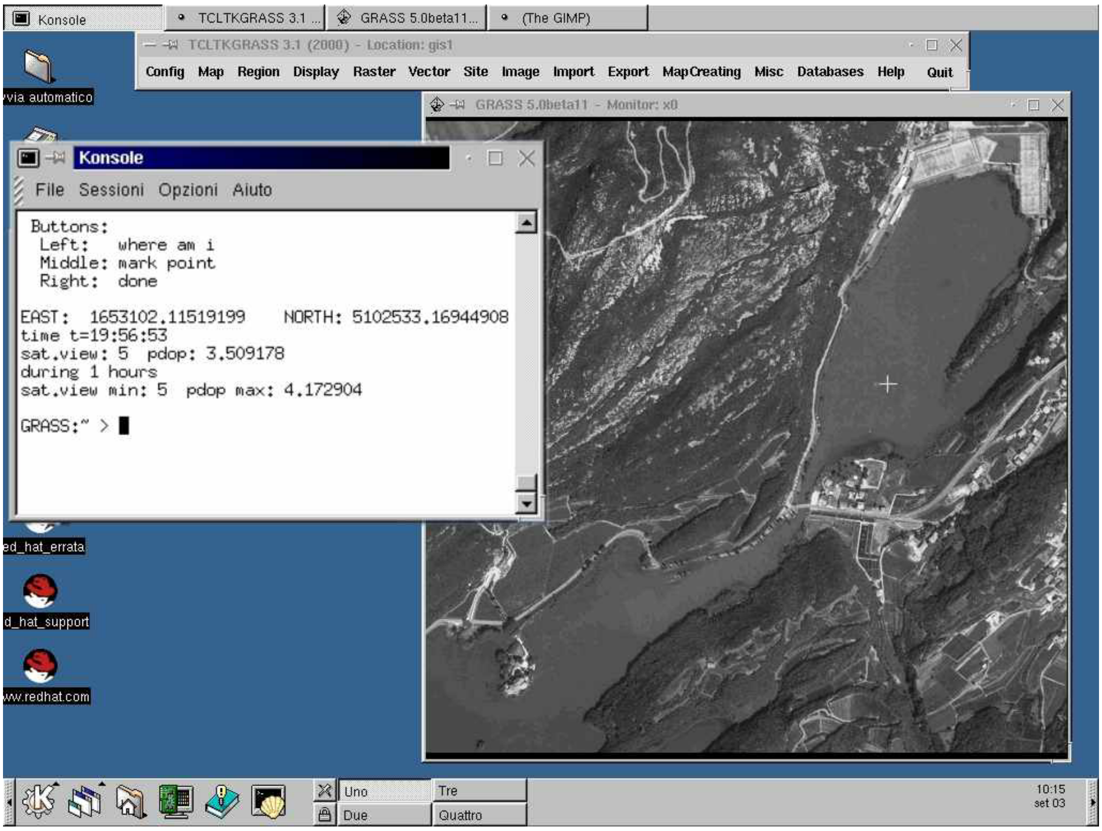
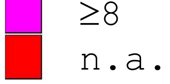
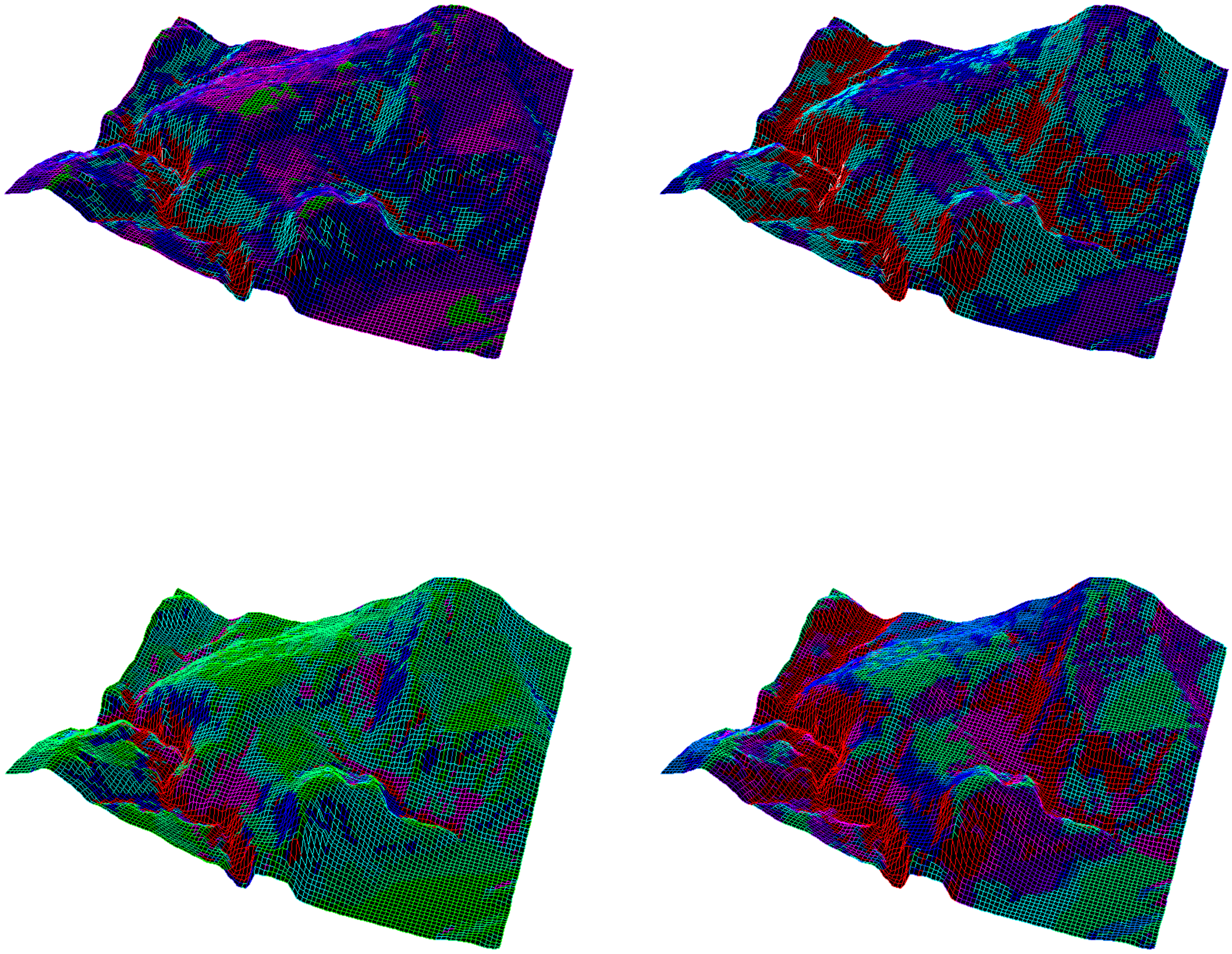


Figure 2 – Static planning for a single pixel.

Figure 3 – Static planning for a whole DTM in the Valle dei laghi area, 20 km east of Trento (Italy) at 19:56:53 of the 2nd of April 1998. Clockwise from the upper left image: number of visible satellites at starting time, minimum number of visible satellites over the planning time span, maximum PDOP values over the planning time span and PDOP values at starting time.





The number of visible satellites and the value of the PDOP parameter at the beginning of the planning and the worst (maximum) values over the time span are provided (figure 2).
In the second case, when the planning is performed of the whole area covered by the DTM, four maps are provided, representing the number of visible satellites and the PDOP values in each raster cell at the beginning of the planning and the minimum number of visible satellites and the maximum of PDOP value over the planning time span.

The **r.planning.cinematic** module performs a cinematic planning. Input data carry information about surface geometry, satellites' positions, trajectory, starting time of planning and speed of the receiver. Data about the surface and the satellites' positions are the same as for r.planning.static, this includes DTM raster data, almanac, reference ellipsoid and cut-off angle.
The path of the receiver during the cinematic survey is given by a (2D) vector file, which can be digitized using the v.digit GRASS module if needed. The trajectory is followed in the order of the vertexes of the polyline, the time is given as starting time (time on the first point) and mean speed. The time on each point is determined using the starting time, the given speed and the distance from the previous vertex.
It is possible to perform a cinematic planning for a trajectory with constant height or with a different height for each vertex: in the first case only one height value must be supplied, while in the latter the module interactively asks at runtime the height for each trajectory point. The output is given as a GRASS *site* data file, i.e. a vector file containing points. Each point is associated, besides

it east and north coordinates, the time of occupation, the number of visible satellites, the PDOP value and its height. The complete synopsis is the following:

```
r.planning.cinematic [-abc] almanacco=name raster=name vector=name
                     site=name  date_time=name  [ellipsoid=name]  [cut_off=value]
                     [speed=value]
Flags:
  -a   3D trajectory at variable height
  -b   2D trajectory at variable height
  -c   (y)=almanac file from net  (n)=rinex format almanac
Parameters:
    almanac   name of GPS file almanac
     raster   raster file which contain the trajectory
     vector   trajectory vector file
       site   site output file
  date_time   Date and time of planning ( ex. 3 Jan 1984 16:33:45 )
  ellipsoid   ellipsoid name
              default: hayford
    cut_off   cut off angle
              options: 0-90
              default: 10
      speed   speed of vehicle (Km/h)
              default: 10
```

The GRASS modules described here are available under GPL license on the web at the address http://www.ing.unitn.it/~zatelli/software_en.html.

6. Applications

A first series of tests on the modules has been carried out comparing the results of the planning to those resulting from commercial software.

The static planning module has been used to evaluate the possibility of using the GPS to track the movements of wild bears in the east of Trentino (Italy). The project "Life ursus – tutela della popolazione di orso bruno del Brenta" (Life ursus – protection of the brown bear population of the Brenta region) routinely traces the position of wild bears using radio collars. This procedure is very burdensome since each bear must be followed by different teams that survey its position twice a day by triangulation. The use of radio collars with GPS receivers would remarkably simplify this procedure. While devices like GPS radio collars are nowadays available, the main problem of this particular use of GPS is that wild bears usually dwell in areas where obstacles to the view of the sky are relevant.

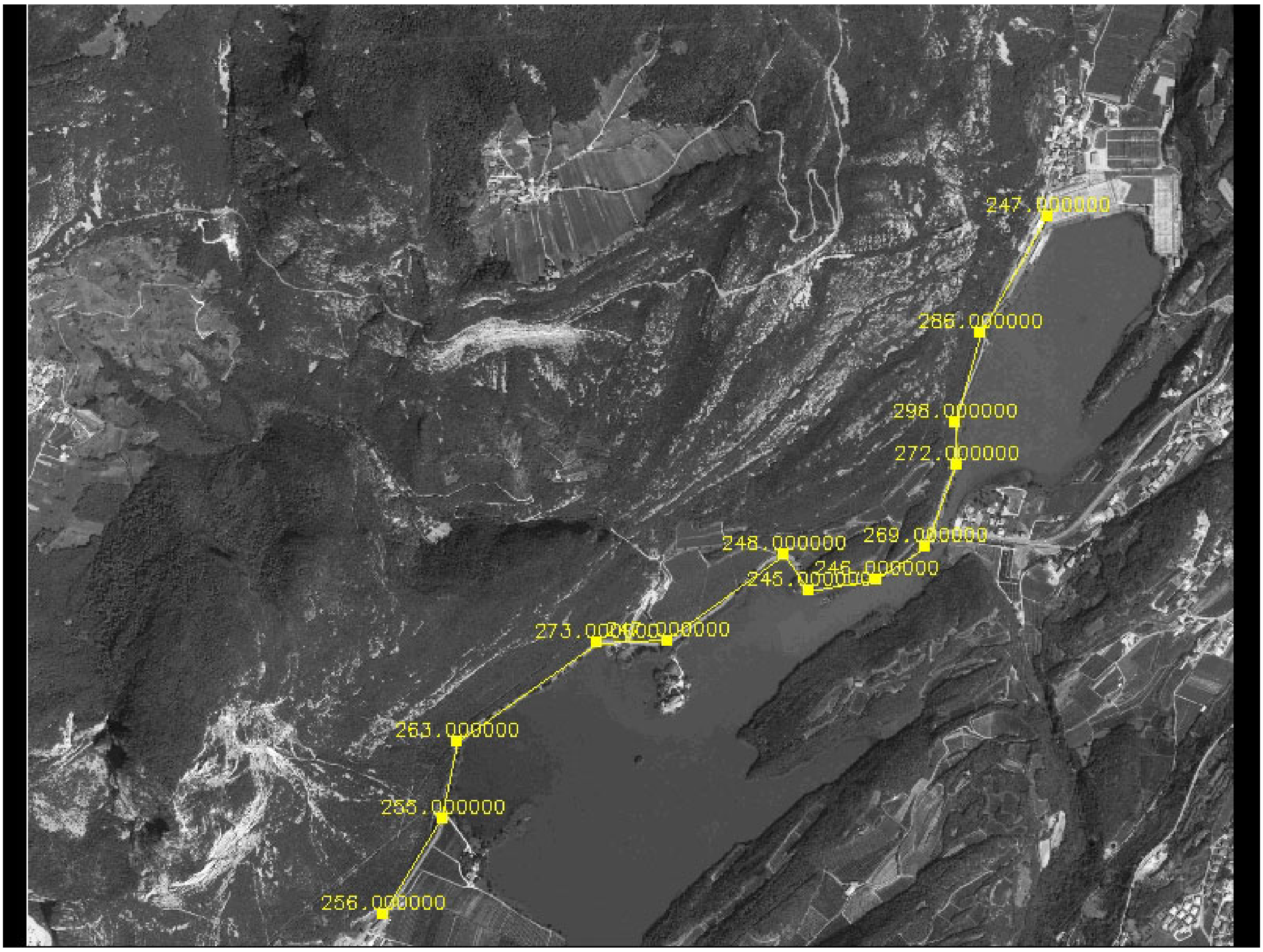


Figure 3 – Cinematic planning for a trajectory in an the Valle dei laghi area, 20 km east of Trento (Italy) starting at 19:56:53 of the 2nd of April 1998. The heights of the points are shown.

The new GRASS modules have been applied to verify the feasibility of the use of this kind of devices. The satellites' visibility and PDOP values have been estimated for an area on the west side of the Paganella mountain (a few kilometers east from Trento) the first of April 2001. During this period a wild bear, tracked using a traditional radio collar, has moved in this area. Since the tracking with radio collars is done by two different position determinations at dawn and at sunset, two different plannings have been performed with a three hours duration starting from 6 am and 8 pm respectively. Series of maps have been produced, showing the number of visible satellites at starting time, the minimum number of satellites over the planning time span, the PDOP values at starting time and the maximum PDOP values over the planning time span for the two periods of the day.

These maps have highlighted the fact that, while a sufficient satellite visibility was not guaranteed over the entire periods (see for example figure 5), some short time intervals would have provided a suitable satellite coverage. Some of these intervals had a length and a number of visible satellites sufficient for the determination of the receiver position with a precision compatible with the requests of the Life ursus project.

Therefore this tool, allowing the realistic planning of satellite surveys, is crucial for this kind of applications, since the correct choice of the time interval is critical. As an alternative, it would be necessary to record the receiver's data continuously over the entire day to be sure that a suitable interval for the position determination is present.

Figure 4 – 3D view of the east side of the Paganella mountain.

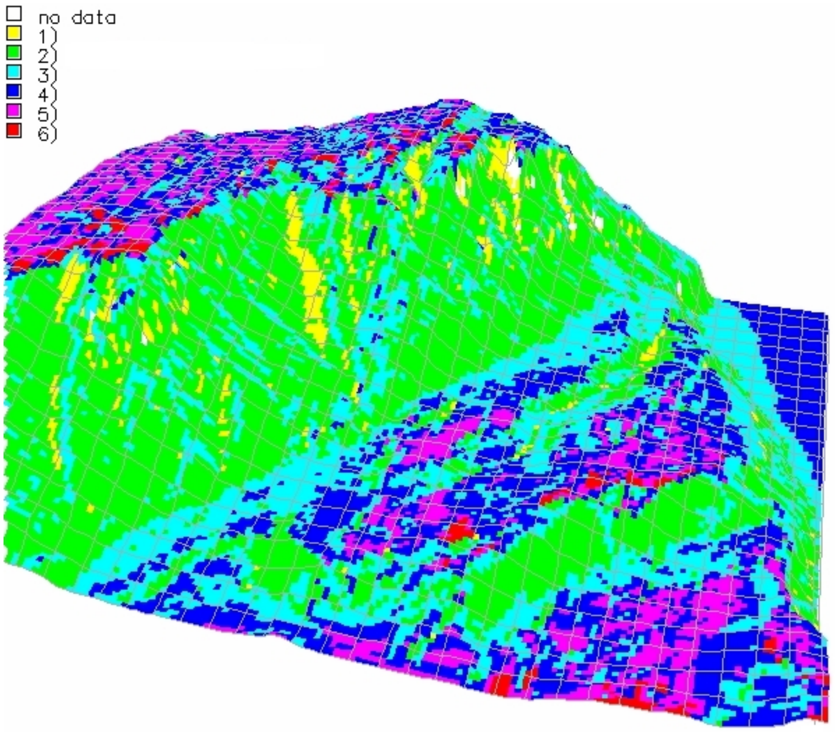


Figure 5 – Minimum number of visible GPS satellites on the east side of the Paganella mountain between 6 and 9 am, 1st of April 2001.

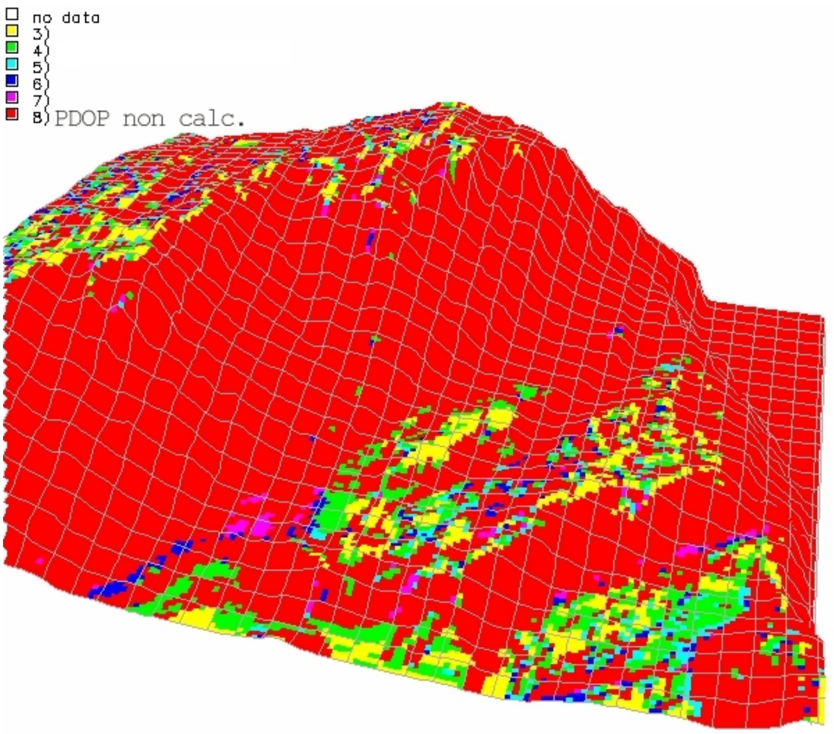


Figure 5 – Maximum PDOP values on the east side of the Paganella mountain between 6 and 9 am, 1st of April 2001.

The cinematic planning module has been used to help the design of flight paths for airborne measurements in the atmospheric boundary layer, for the development of local meteorological models (de Franceschi et al., 2002). Moreover, the trajectory of a car in an alpine valley has been simulated to investigate the feasibility of car navigation using GPS positioning in mountain areas.

7. Conclusions

The development of three new GRASS modules for the planning of satellite surveys can help all the activities which use these techniques to georeference information.
The integration of this tools in a GIS offers several advantages such as:

- the possibility of operating in an environment suitable for the management of geographical information;
- the possibility of integrating the results of these tools with other analyses;
- the use of a common data and user interface.

Further developments will include the possibility of make use of the new 3D GRASS vector format to describe a 3D trajectory.
Moreover, the use of these GRASS modules for the planning with respect to satellite position system other than GPS, like GLONASS or the forthcoming European Galileo system.

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Bibliography

CARLI D., FRUET G., SGUERSO D., ZATELLI P., 2000 - *Nuovi sviluppi per la pianificazione di rilievi GPS cinematici terrestri ed aerei*. Atti del convegno "4a conferenza nazionale delle

associazioni scientifiche per le informazioni territoriali e ambientali", Genova, 3-6 October, 2000, ASITA:Genova, 2000, Vol. 1, pp. 501-502.
CIOLLI M., SGUERSO D., ZATELLI P., 2000 - *GIS applications with GRASS. Geomatics workbooks*, 2000, Vol. 1, pp. 61-72.
DE FRANCESCHI M., RAMPANELLI G., SGUERSO D., ZARDI D., ZATELLI P., 2002 - *Development of a measurement platform on a light airplane and analysis of airborne measurements in the atmospheric boundary layer*. Annali di geofisica, 2002, in print.
D'INCA' D.., 2000 – *Procedure ed algoritmi innovativi per la pianificazione di rilievi satellitari in ambiente GIS GRASS*. Graduate thesis, Engineering Faculty, University of Trento, Italy.
FRUET G., SGUERSO D., ZATELLI P, 1999 - *Planning GPS automatico con ostruzioni realistiche.*. Atti del convegno "3a Conferenza nazionale delle Associazioni Scientifiche per le Informazioni Territoriali ed Ambientali", Napoli, 9-12 November, 1999, ASITA:Napoli, 1999, Vol. 2, pp. 773-778.
GRASS DEVELOPMENT TEAM 2001 – GRASS 5.0 Programmer's Manual – 19th February 2001
SGUERSO D., ZATELLI P., 1999 - *Planning of kinematic GPS including realistic obstacles description*. Presentation to the XXII General Assembly of IUGG, Birmingham, 19-30 July 1999.

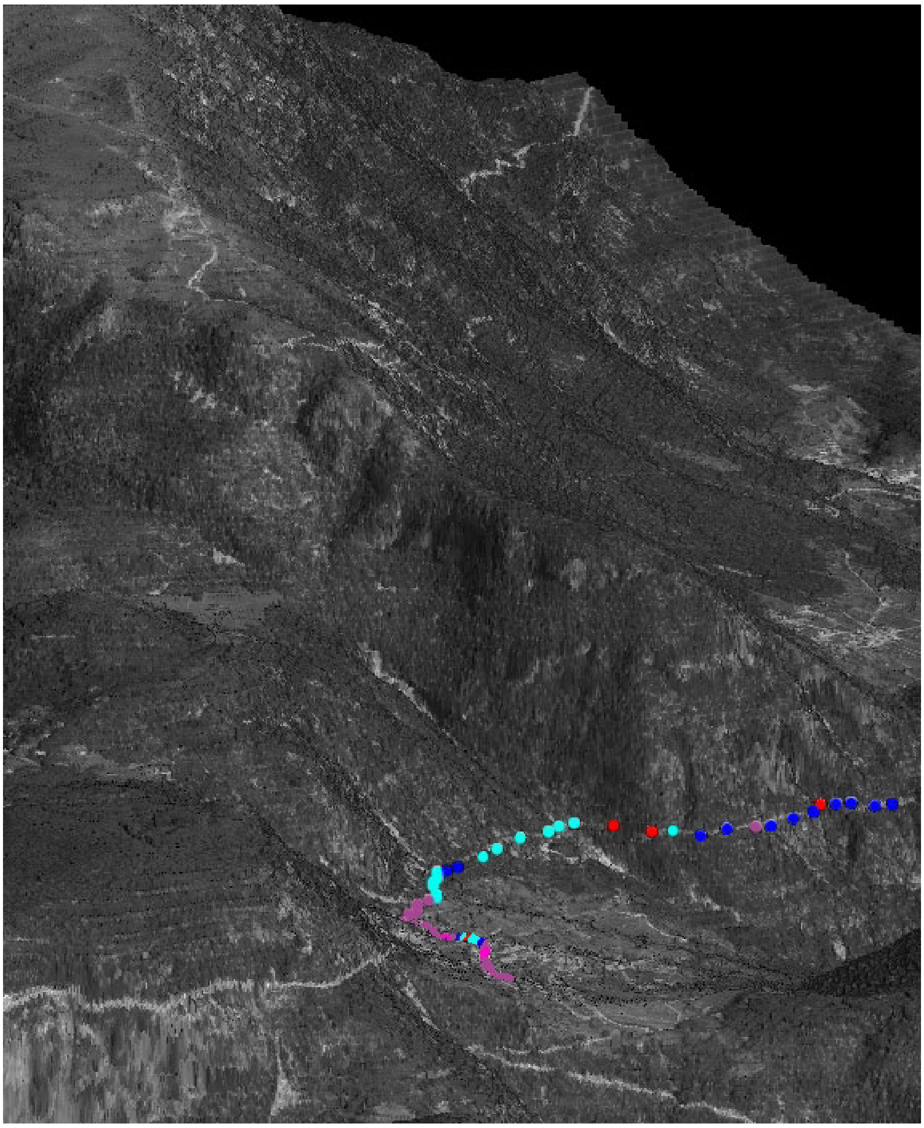

Figure 6 – Cinematic planning for a trajectory in the Valle dei laghi area, 20 km east of Trento (Italy) starting at 19:56:53 of the 2nd of April 1998. The dots represent the points where the number of visible satellite has been evaluated, colors correspond to the number of visible satellites: red less one, cyan 4, blue 5, purple more than 6.