ImPredict: a Fast Image Prediction Software and Its Application in the SSTL off-axis Image Scheduling System

S.-F. Wu, A. Brewer, P. L. Palmer

Surrey Space Centre
Surrey Satellite Technology Limited (SSTL)
University of Surrey
Guildford, GU2 7XH, United Kingdom

Abstract

A major cost saver in low-cost missions is reducing operation costs. This paper outlines the work carried out at Surrey Space Center (SSC) to reduce the time required to generate image schedules for tasking the remote sensing satellites. The principle and basic algorithms of an innovative imaging prediction approach are first briefly presented, which result in a fast imaging prediction software, the ImPredict. Experiment results show that its prediction speed is several orders of magnitude faster than the traditional trajectory-checking approach while keeping an even better accuracy. The software has currently been implemented as windows DLL, written in 'C', which has been linked into the SSTL off-axis scheduling system for practical application for the UoSAT-12 and Tsinghua-1 missions. Its future applications for formation satellite missions are further prospected.

1 Introduction

Over the last few years it has been shown that low cost small satellites are now suitable platforms for useful Earth observation (EO) missions. In line with the philosophy of "better, faster, and cheaper", the ground-segment and operations must also be addressed. Appropriate planning tools are required, that cut down the amount of user inputs required, but also matches the mission in terms of complexity.

To meet the imaging scheduling requirements primarily for the UoSAT-12 mini-satellite and Tsinghua-1 micro-satellite, a software tool was recognized to be required, with the following functional abilities:

- ***Fast calculation of suitable passes***

This is required for rapidly calculating passes opportunities over a list of ground targets that are required by users.

- ***Prediction of imaging opportunities with available attitude maneuvers***

As both of the satellites have limited swath widths, they may not fly directly over the desired target area for some periods (days or weeks). In-orbit attitude maneuvers are used to point the camera at the target to get more opportunities for imaging. Both of these missions have off-axis imaging capabilities, but the implementation is different. The Imaging system on UoSAT-12 is nadir pointing, but can be rolled off to a specified angle. Tsinghua-1 has a novel approach by canting the camera off to a 19° fixed angle. The off-axis imaging can be achieved either using roll or yaw maneuvers. We needed ways to calculate the angles to off-point the spacecraft.

- ***Calculation of Sun angle at the predicted imaging chances***

This is required to adjust the camera settings in order to maximize the use of the camera's dynamic range.

- ***Generating schedules for spacecraft***

An easy way to take the output from the orbit modeling software and use this to task the spacecraft with minimum of user intervention was required.

To meet these requirements, new innovative techniques and algorithms to speed up the prediction process have been explored and developed recently in Surrey Space Center, to solve both the traditional rise-and-set time problem (satellite pass prediction) and the imaging prediction problems for LEO satellites subjects to a canted camera and available attitude maneuvers[3-7]. These research results have been further incorporated into a computer software tool, the ImPredict. It has five working modes, to predict respectively: (1) the satellite rise-and-set time and maximum elevation angle and time, (2) imaging opportunities with a canted camera without attitude control (the nadir pointing camera becomes a special case with 0 cant angle), (3) imaging opportunities with a canted camera and available yaw maneuvers, (4) imaging opportunities with a canted camera and available roll maneuvers, (5) image

projection onto the Earth's surface at a given time and specified satellite attitudes. Meantime, the expected Sun angles with respect to the specified target at the predicted time are also calculated.

Additionally, the relatively low cost of small satellite technology allows deployment of multi-satellite constellations, which have potential advantages for certain types of EO science missions where frequent revisits to the same target area are required. One example is the Disaster Monitoring Constellation (DMC)[1], which is made up by five low cost enhanced microsatellites, aiming at the first low-cost and integrated Earth observation constellation in the world dedicated to the humanitarian objectives of disaster assessment and monitoring. Another proposed satellite network is the "GANDER" mission[2], which will comprise a constellation of 16 microsatellites, aiming at providing commercial services on predictions and forecasts of maritime conditions through measuring the significant sea wave height and sea surface wind velocity.

For these kinds of more complicated space missions, greater operability and on-board autonomy of satellites become crucial to reduce the cost, for both ground and on-board operations. The algorithms and ideas developed here are being expanded to address these needs. Details of some idea of the future work are outlined here.

This paper aims to outline the research results and applications of this fast imaging prediction software tool. Section 2 describes the prediction principle and the basic algorithms. Section 3 discusses the software design and performance evaluation results. Section 4 describes the integration of the software into SSTL's imaging mission scheduling system. Section 5 presents some in-orbit application results. Section 6 prospects its future application in satellite constellation missions of SSTL. Section 7 summarizes the major results of this paper.

2. Prediction Principle and Algorithms

The task of imaging prediction is to find the potential time points when the satellite is in a best position to take images on a specified ground target subjecting to certain conditions. In ImPredict, this complicated task is divided into three successive steps. First, a coarse search process is applied to find out the potential satellite passes that offer possible imaging opportunities. Then, an imaging estimation process is adopted to estimate the appropriate imaging time based on the coarse search results and the spherical geometry, as well as the target and satellite orbital information. In the above two steps, the Earth is regarded as an ideal sphere and the satellite's orbit is treated as a circle, which would bring errors in the estimation results. Computation results showed the errors are normally within the range of a few seconds (1-3 seconds) for LEO satellites[5]. An imaging refinement process is finally taken to compensate for the errors in the estimation results. Accurate satellite orbital solution and practical Earth shape model, together with the target parameters, are used to solve the conditional equations of the imaging point. For each imaging prediction mode, appropriate iteration algorithms are developed to get the specified prediction accuracy.

2.1 Coarse Search Principle

The basic principle of the coarse search algorithm is the fact that for two-body motion a satellite will revisit exactly the same point in an inertial co-ordinate system after each orbital period T[3,4], as illustrated in Fig.1.

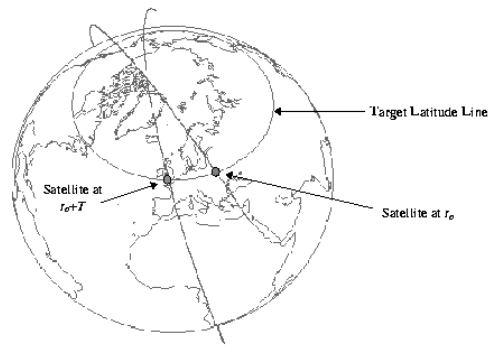


Figure 1: Movement of satellite footprint along TLL when orbiting around the Earth

While the Earth rotates along its eigen axis, the target will move along the target latitude line (TLL), which is defined as the small circle of constant latitude that runs through the target location. Thus in the inertial space after each orbital period that the satellite revisits the TLL, the Earth's rotation will bring the target closer to the satellite's longitudinal position along the TLL. In other words, the satellite will see the target approaching by an amount $\omega_{\oplus}T$ or $\omega_{\oplus}2\pi/n$, where $\omega_{\oplus}$ is the Earth's rotation rate, n is the orbital mean motion, and T is the orbital period. In the Earth centered Earth fixed (ECEF) coordinates, the target will see the satellite's longitude at TLL crossing approach or leave from the target longitude with a step of $\omega_{\oplus}T$ after each orbit. This relation could be described by the following equation,

$$\Delta\upsilon = \upsilon_S - \upsilon_T = N\omega_{\oplus}2\pi/n + d\upsilon \qquad (1)$$

where $\Delta\upsilon$ is the initial longitude difference between the satellite footprint (υ_S) when first crossing the TLL

at time t_o and the specific target on the ground (υ_T), N is the number of satellite revolutions since t_o, $d\upsilon$ is the longitudinal difference angle between satellite footprint and target at time $t = t_o + NT$.

This equation builds up a very simple and fast relation between the target and satellite footprint longitudes as a function of time, which forms the core part of the fast coarse search algorithms for satellite passes. To account for secular perturbations and drag effects, some modifications were introduced to the above equation, details can be found in the references[3,4].

On the other hand, the finite field of view (FOV) of the camera will cover a certain belt on the Earth's surface as a satellite flies along its orbit, as illustrated in Fig.2a, where τ represents the canted angle of the camera with reference to the nadir direction, γ is the camera's FOV. The border of the imaging swath can be represented by the angles θ_1 and θ_2, which are calculated by the following equations,

$$\theta_1 = \sin^{-1}\left(\frac{R+h}{R}\sin\left(\tau - \frac{\gamma}{2}\right)\right) - \left(\tau - \frac{\gamma}{2}\right) \qquad (2)$$

$$\theta_2 = \sin^{-1}\left(\frac{R+h}{R}\sin\left(\tau + \frac{\gamma}{2}\right)\right) - \left(\tau + \frac{\gamma}{2}\right) \qquad (3)$$

where R is the Earth's radius and h is the satellite altitude. As both R and r change as the satellite moves along its orbit, these two angles are not constants in time. However, for LEO Earth observation satellites, their orbits are normally near circular and polar. For simplicity, the orbital semi-major axis and the Earth's equatorial radius are used in the above equations to get constant offset angles.

To connect the imaging border angles with the satellite longitude position along TLL, the border angle θ is further transferred as a longitude offset angle $\Delta\upsilon$ along the TLL, as shown in Fig.2b. With the known target latitude ϕ and satellite inclination angle i, a set of algorithms based on spherical trigonometry relations were developed to transfer the border angle θ_1 and θ_2 into longitude offset angles $\Delta\upsilon_1$ and $\Delta\upsilon_2$, see reference [4-5] for details.

From the relative motion between the target and satellite footprint along TLL, when the angle difference between the longitudes of the target and satellite footprint on TLL meet the following relation,

$$\Delta\upsilon_2 \geq d\upsilon \geq \Delta\upsilon_1 \qquad (4)$$

the target will be within the camera's FOV in width, which means a potential imaging opportunity arises. Thus the approximate time (or phase angle) of the satellite as it passes through the TLL within a relevant longitude range can be determined rapidly, without involving the satellite's orbital propagation equations.

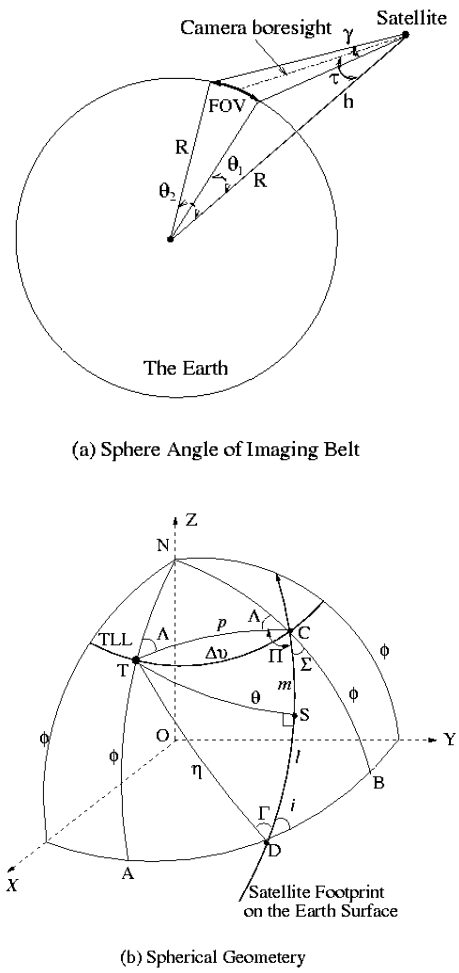


Figure 2. Coarse search and imaging estimation geometries

2.2 Imaging Estimation Algorithms

After the coarse search process, the relevant satellite passes are determined in the form of the times of TLL passage. The next step is to determine the imaging position subject to different imaging modes. For the second working mode, without attitude control, the imaging point should be located near the point S in Fig. 2b, where the great circle connecting S with the target should be perpendicular to the orbital plane CD. Again the Earth is assumed to be an ideal sphere, and the spherical trigonometry relation is used to compute the arc length CS (i.e., the spherical angle m) from the known latitude off-set $\Delta\upsilon$ (equal to $d\upsilon$ in equation (4)) with appropriate algorithms[5].

Thus the estimated imaging point S can be determined as,

$$\alpha_S = \alpha_C + m \quad (5)$$

where α_S and α_C represent the epicycle phase angle of the satellite at the points S and C.

For the working mode with available roll attitude control, the perpendicular point S is also the approximate imaging point. However, for the working mode with available yaw manouver, the perpendicular point S would not be the approximate imaging point anymore, thus new imaging conditions and algorithms are developed to estimate the imaging points under different circumstances, see reference [5] for details.

2.3 Imaging Refinement Algorithms

To refine the estimation results, accurate satellite orbit propagation is required to get the exact satellite position and velocity information at the time of interest. The following epicycle equations[6, 7], which use four redundant coordinates to describe the satellite's orbital propagation, are used in the refinement algorithms,

$$r = a(1+\rho) - A\cos(\alpha - \alpha_p) + a\chi \sin\beta + a\Delta_r \cos 2\beta - 2B\beta \quad (6)$$

$$i = i_0 + \Delta_I (1 - \cos 2\alpha) \quad (7)$$

$$\Omega = \Omega_0 + \theta\alpha + \Delta_\Omega \sin 2\alpha \quad (8)$$

$$\lambda = \beta + \frac{2A}{a}[\sin(\alpha - \alpha_p) + \sin\alpha_p] - 2\chi(1-\cos\beta) + \Delta_\lambda \sin 2\beta + \frac{3}{2}B\beta^2 \quad (9)$$

$$\beta = (1+\kappa)\alpha = (1+\kappa)nt \quad (10)$$

where r is the satellite radius to the Earth's centre, i inclination, Ω the right ascension of the ascending node, λ the argument of latitude, ρ, κ and θ are coefficients for secular perturbation, χ is the long periodic perturbation coefficient, Δ_x represent the short periodic terms, and B is the epicycle drag coefficient. For a LEO satellite with its orbit eccentricity being not larger than 0.005, the above epicycle equations give a direct solution of the satellite position with reference to time, with a better accuracy than the results by using the SGP4 propagation approach[6, 8].

As the conditional equation of imaging is not possible to be solved directly through closed algebraic relations, iteration algorithms are developed to get the required accuracy for different circumstances.

The satellite's coordinates are given as a function of time from the above equations in the local orbit (LO) coordinate frame, and are then transformed into the Earth centered inertial (ECI), Earth centered Earth fixed (ECEF) and local tangent (LT) coordinates successively. Meantime, the unit orientation vector of the camera's boresight is calculated in the satellite body axes, according to the given information (canted angle, etc), and is then transformed into the LO, ECI, ECEF, and LT axes successively. The iteration process on the imaging conditional equation is conducted within the LT coordinate frame. The basic principle is to calculate the time off-set value between the current predicted imaging point and the ideal imaging points, based on the imaging conditional equation. Then this time off-set is added onto the predicted imaging point to get a new evolved prediction improve its accuracy. Iteration process based on this principle is applied, until the time off-set become smaller than the specified time accuracy tolerance. As the algorithms are not the emphasis of this paper, they are not discussed here. Readers are suggest to refer to reference [5] for details.

3. Software Design and Performance Evaluation

Based on these algorithms, the software package, ImPredict, has been developed with standard C language in Unix environment. It comprises all the five working modes as discussed in this paper. It reads NORAD orbital data file and translate the two line of elements into epicycle elements[7]. Then based on the assigned target information and working mode choices, all the potential imaging chances will be predicted and sorted out. Computation results for both Tsinghua-1 and UoSAT-12 showed all the algorithms developed in this paper have good estimation accuracy and fast convergence. After the coarse search and estimation algorithms (step 1 & 2), the estimated imaging times are within a few seconds (1-3 seconds) of the actual times. With the iteration algorithm discussed above (step 3), the time accuracy could reach to 0.02 seconds within 2-3 rounds of iteration.

Illustrated here is some test computation results with ImPredict. The NORAD orbital data file of Tsinghua-1 on Sept. 6, 2000 (Epoch time: 11:42:58.31 on 05/09/00) is set as the orbital input, the searching time window is set as 7 days. The camera's FOV is set as 15 degree. The ground target is chosen as Guildford, UK (latitude 51.2 deg, longitude 359.41 deg, height 0 m). The error tolerance for estimation refinement is set as 0.02 seconds. Table 1 lists the resulting opportunities found for different working modes. Table 2 lists some detailed prediction results at two working modes.

From Table 1, for a time span of one week, there were 52 visible passes over the target, however only 3 passes give chances of imaging with a nadir tracking

camera. When the camera is canted with –20 degrees, only two passes give imaging opportunities. By using yawing control, the imaging opportunities are increased to 12 from 7 passes. Similarly, with a maximum roll maneuver of 27.5, all the 7 passes give 7 imaging chances. When the maximum roll angle is reduced to 20, the imaging chances are reduced to 5, i.e., 5 passes are within the canted angle of 20 deg, which contribute two imaging chances in the mode with yaw control.

The prediction accuracy in space is evaluated by checking the miss distance between the target and the camera's boresight shadow point in the LH plane at the predicted time, using the working mode 5. That is, with the predicted time and attitude information, the imaging projection point on the Earth's surface is calculated and compared to the specified target position. Results showed that with yaw maneuvers the miss distances are within 0.1 meters for the cases when the camera is able to point at the target. With roll maneuvers, the miss distances are within 20 meters. This estimation accuracy is good enough for Earth observation missions.

To evaluate the efficiency in computational burden, a comparison test has been done between ImPredict and the old software used previously by SSTL, which was developed based on the trajectory checking approach by using the SGP4 propagation model[8] with a constant time step. Both algorithms are run on the same PC with a Pentium III processor of 500MHz, to predict imaging opportunities for 433 targets around the world in a time span of 7 days with the orbital data of Tsinghua-1. The time step for the old software was set at 1 second, which means the timing accuracy of the prediction results is within 1 second. The time tolerance for the ImPredict was set as 0.02 second. Results show that for the same working mode (nadir imaging), the new software is approximately 1000 times faster than the old software (0.6 seconds versus 590 seconds). For the more complicated working modes with attitude controls, the old software can not provide estimates for comparison. Compared to itself, the computation time is approximately 30-50% larger than that for the nadir imaging mode with the software ImPredict. Additionally, to achieve the same timing accuracy, the time step for the old software should be reduced to 0.02 seconds, which means its computation time would increase roughly 50 times. This comparison test indicates the significant improvements of the new algorithms in both accuracy and speed.

4. Integration into the SSTL off-axis Image Scheduling System

The system described here was developed to provide an easy way of generating the tasking schedules for the imaging systems on the Tsinghua-1 micro-satellite and UoSAT-12 mini-satellite. It is primarily designed for satellite mission operators, who would use this system to generate the schedule for the upcoming week. As part of the low cost approach, a quite simple software was developed to address the immediate needs of the operator. It is assumed that the operator is aware of limitations on Imaging, such as limit of the number of Images and other conflicting operations.

The main tool of the system was named ImTarget and was written in Visual Basic as this was suitable for database access. The ImPredict prediction code was written in 'C' as a DLL, so it could easily be called from applications written in a range of languages. It also provided a clean interface between the application and the prediction code, which helped during development and has benefits for reuse. Other tools were written to manipulate the contents of the various databases that store information relevant to ImTarget.

Figure 3 shows the data flow through the application. Users start with the Search form as shown in Figure 4. The user selects the payload and satellite from the list. This list comes from a database, which also stores all the payload parameters such as view angles and ADCS modes. The user can enter the number of days to search and the start time and date. The targets that are searched come from a database of targets or a single target may be specified.

The application then passes all the information about the search to the Impredict search DLL, which returns all the possible results. These are displayed in the results window as shown in Figure 5.

The operator can then create a tasking schedule by selecting entries from the 'possible targets' window and adding them to the 'Schedule' window. The parameters for each event in the schedule can be selected from a list of modes. When modes are selected this actually links to a command list. This command list links together a series of spacecraft commands to be executed at fixed relative times. After the operator has created the tasking schedule, to execute it on the spacecraft the operator selects 'generate satellite files' from the menu system.

Imtarget then generates all the command files for the spacecraft and passes this file to the upload directory within the Surrey groundstation. When the spacecraft comes into range the file is uploaded and automatically run. After Image capture, the files are also automatically downloaded.

The on-board software performs checks on the commands, to ensure that there are no conflicts

between different events, and also implements a basic priority system.

Table 1 *Passes/Imaging Chances at Different Working Modes*

Mode & Parameters	Visible Passes	Nadir Imaging	Canted at –20 deg	Canted at –20 deg with Yaw	With Roll Φ_{max}=20 deg	With Roll Φ_{max}=27.5 deg
Opportunity Number	52	3	2	12 (7 pass)	5	7

Table 2 *Imaging Prediction Results at two Working Modes*

	Nadir Imaging (Canted at 0 deg)			Canted at –20 deg	
Imaging Time	03:06:49.67 06/09/2000	13:44:14.08 10/09/2000	03:14:58.22 11/09/2000	02:50:30.62 08/09/2000	14:00:32.03 08/09/2000
Elevation Angle (deg)	83.6675	82.2879	83.4948	60.4456	73.0922

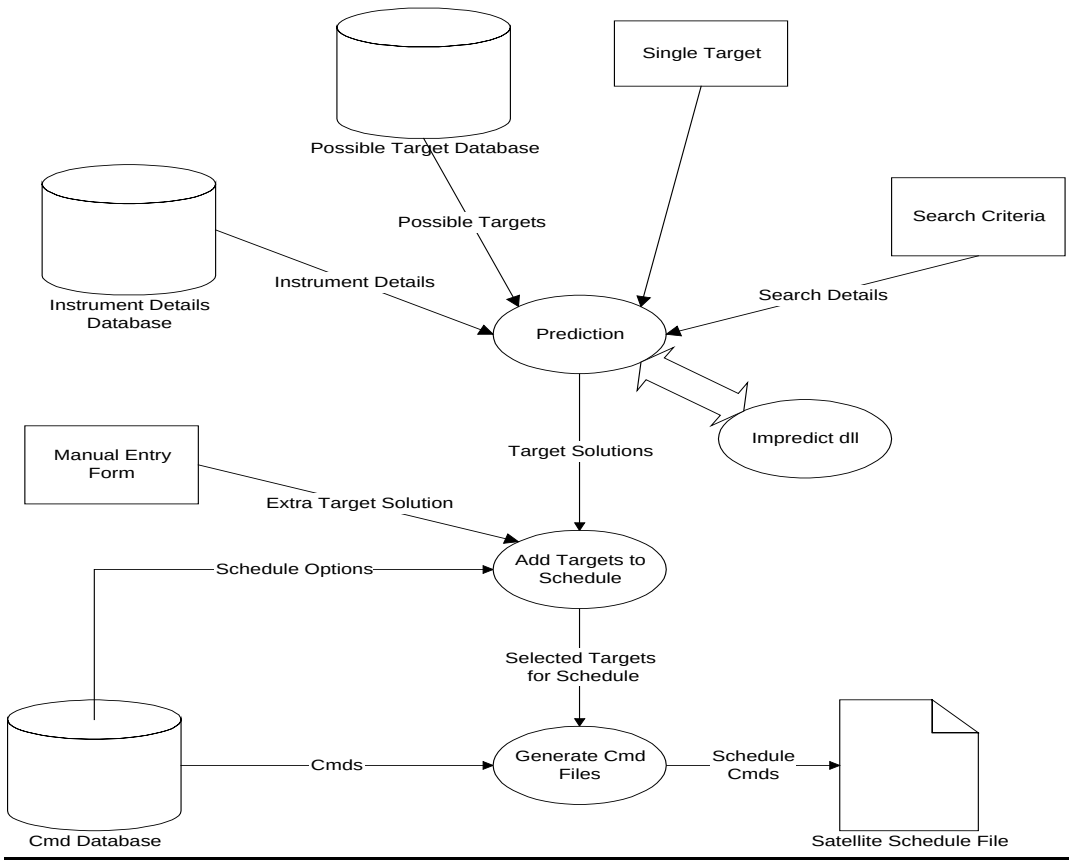


Figure 3 ImTarget Data Flow

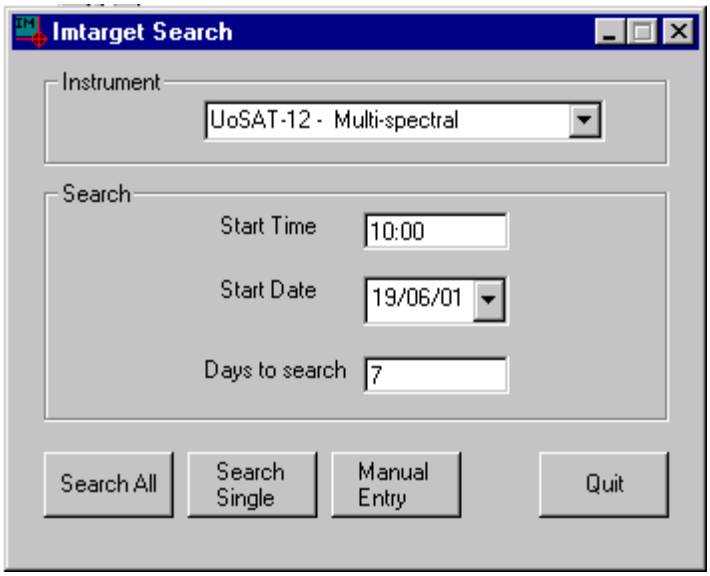
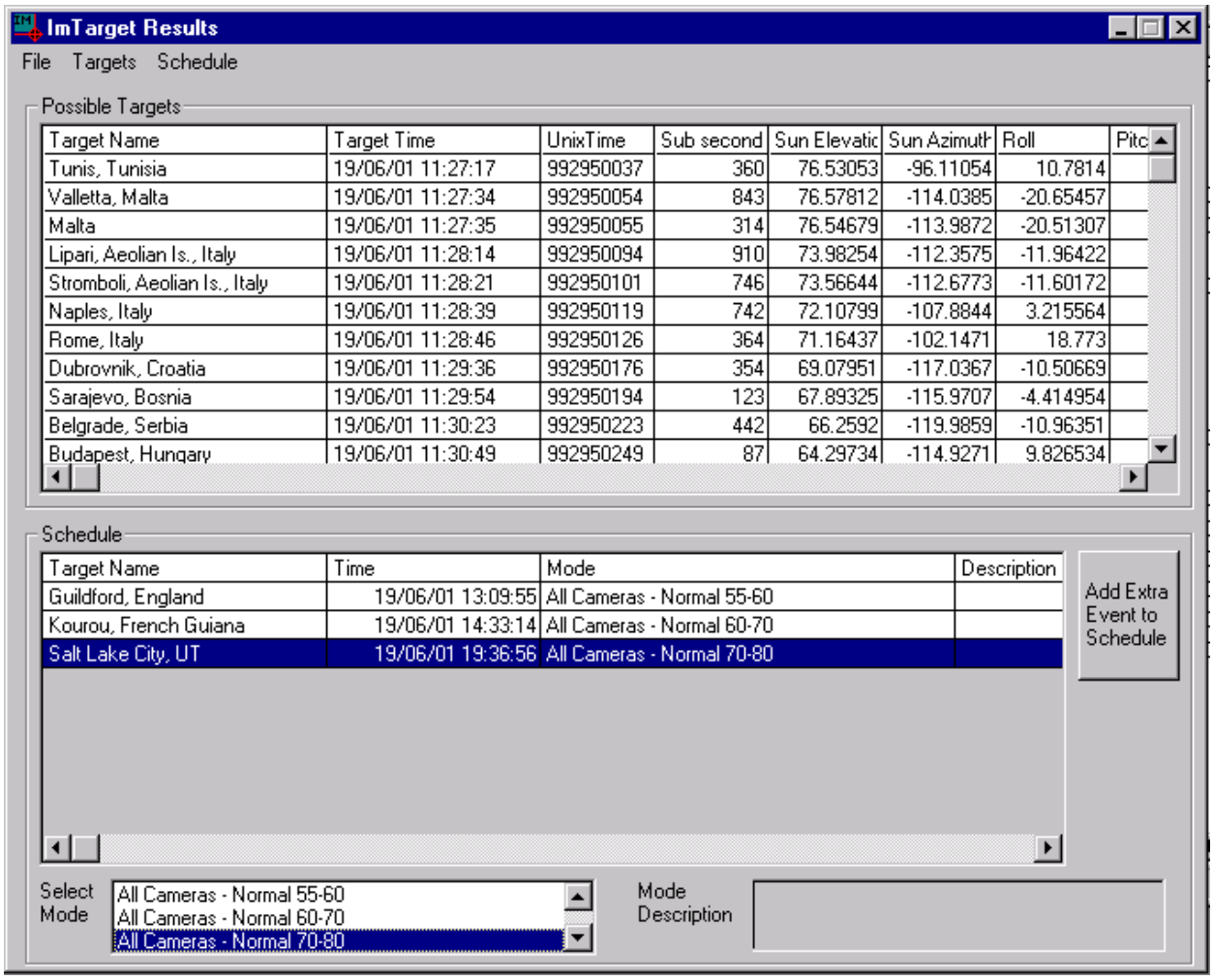


Figure 4: Imtarget Search Screen



Target Name	Target Time	UnixTime	Sub second	Sun Elevatic	Sun Azimuth	Roll	Pitc
Tunis, Tunisia	19/06/01 11:27:17	992950037	360	76.53053	-96.11054	10.7814	
Valletta, Malta	19/06/01 11:27:34	992950054	843	76.57812	-114.0385	-20.65457	
Malta	19/06/01 11:27:35	992950055	314	76.54679	-113.9872	-20.51307	
Lipari, Aeolian Is., Italy	19/06/01 11:28:14	992950094	910	73.98254	-112.3575	-11.96422	
Stromboli, Aeolian Is., Italy	19/06/01 11:28:21	992950101	746	73.56644	-112.6773	-11.60172	
Naples, Italy	19/06/01 11:28:39	992950119	742	72.10799	-107.8844	3.215564	
Rome, Italy	19/06/01 11:28:46	992950126	364	71.16437	-102.1471	18.773	
Dubrovnik, Croatia	19/06/01 11:29:36	992950176	354	69.07951	-117.0367	-10.50669	
Sarajevo, Bosnia	19/06/01 11:29:54	992950194	123	67.89325	-115.9707	-4.414954	
Belgrade, Serbia	19/06/01 11:30:23	992950223	442	66.2592	-119.9859	-10.96351	
Budapest, Hungary	19/06/01 11:30:49	992950249	87	64.29734	-114.9271	9.826534	

Target Name	Time	Mode	Description
Guildford, England	19/06/01 13:09:55	All Cameras - Normal 55-60	
Kourou, French Guiana	19/06/01 14:33:14	All Cameras - Normal 60-70	
Salt Lake City, UT	19/06/01 19:36:56	All Cameras - Normal 70-80	

Figure 5. Imtarget Search Results Screen

5. In-Orbit Application

Before spacecraft testing, results from the prediction code were compared with results from running STK simulations and the previously used prediction code.

At the time of writing the whole system presented here is being tested with the UoSAT-12 spacecraft. Already it has been found to vastly reduce the time required to task the spacecraft. The other consequence is it has removed many of the possibilities for user error, so tasking in now more reliable. As UoSAT-12 is primarily an experimental and research mission, rather than a commercial service, the imaging campaign in the past has not fully utilized the resources. Now that the tasking is less of an overhead, the Spacecraft will be used more fully.

Some initial results of the targeting are shown here.

Example 1: **Mui Varella in Vietnam Latitude 12.98 Longitude 109.4**

```
UoSAT-12 two line elements
1 25693U 99021A   01078.25244542  .00000745  00000-0  13283-3 0  6544
2 25693  64.5650 351.8615 0049338 258.6085 100.9476 14.73659318102831
```

Results of Impredict: Date 24/3/2001 Time 03:23:09 Roll:11.2 Sun Elevation 65.7

Figure 6: RGB Image from UoSAT-12

(Note: Image shown to indicate results of pointing prediction. For reasons of size, image quality is reduced.)

Result: In this example the along track accuracy was very close, however the roll is less accurate. The configuration of the ADCS on UoSAT-12 is such that at roll angles above approximately 4.5° the pointing accuracy degrades.

Example 2: Cairo, Egypt Latitude 30.00 Longitude 31.2

```
UoSAT-12 two line elements
1 25693U 99021A   01078.25244542  .00000745  00000-0  13283-3 0  6544
2 25693  64.5650 351.8615 0049338 258.6085 100.9476 14.73659318102831
```

Results of Impredict: `Date 23/3/2001 Time 09:33:39 Roll: -3.4 Sun Elevation 60.3`

Results: The results from this Image were good in timing and roll angle. The Image, as shown in Figure 7, was slightly south of Cairo. This can be explained by the fact that the Latitude entered is also slightly south.

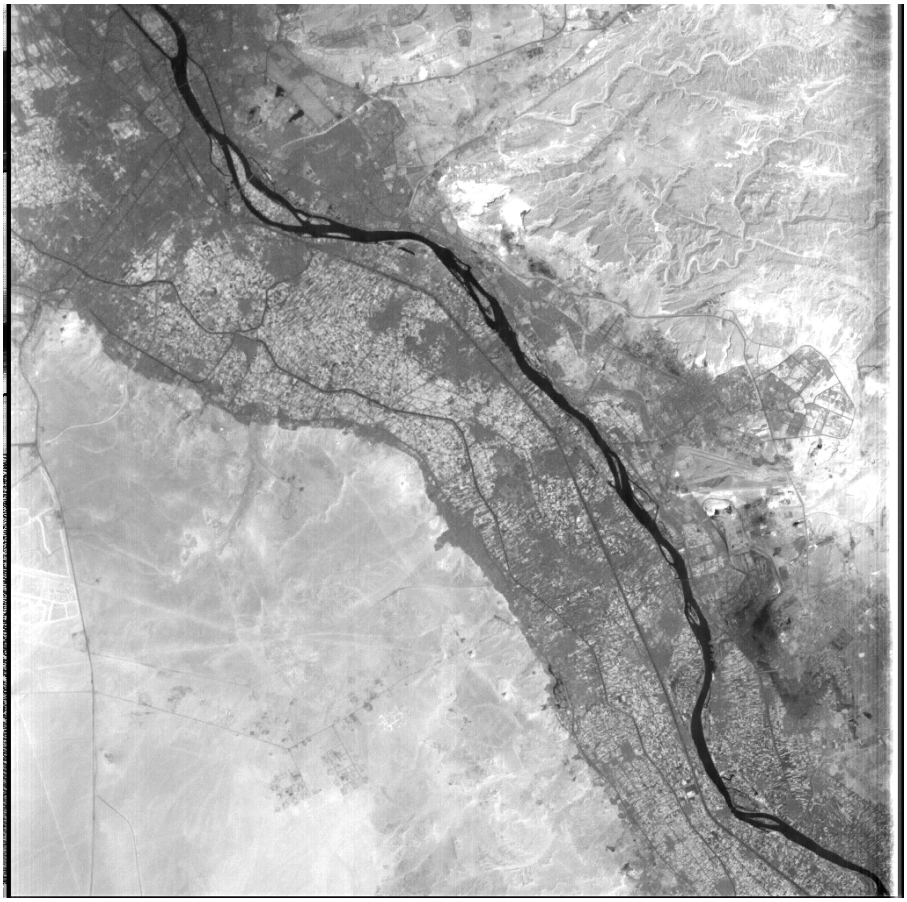


Figure 7. UoSAT-12 NIR Image (32m) of Cairo

The initial results of the two examples presented here are very favorable. When looking at the accuracy, there are other factors that will affect the achieved results. These include:

- ***Timing errors***

There are a number of areas where the timing can be improved. Image capture and the resolution of the clocks on board the spacecraft are to the nearest second. To improve upon this it is proposed to use the on-board GPS receiver to timestamp the image at time of capture.

- ***Attitude errors***

There are attitude errors caused by the ADCS sensors and on-board extended Kalman filter. The current attitude accuracy with UoSAT-12 is in the order of a half degree.

- ***Alignment errors***

UoSat-12 had no alignment tests performed before launch.

The plan is to continue the imaging campaign, to improve the targeting accuracy of the whole system. However ultimately there will be a limit to the degree of accuracy of prediction that we can test for, due to some practical spacecraft limitations.

6. Future Application Prospects

There are many ways that this application can be enhanced, and it is proposed to develop these concepts for future missions such as the upcoming Disaster Monitoring Constellation (DMC). The system is generic in the way it handles commanding of the experiments so can rapidly be set up for different scenarios. As UoSAT-12 is primarily an experimental mission it offers good opportunities for rapidly trying out new operating scenarios on a real spacecraft. In the development of ImPredict, as already outlined, several ADCS modes were implemented, so it is not expected that many changes will be required.

It is anticipated to split ImTarget in two for the DMC[1] and introduce a payload timeline. Users will use the prediction part to work out opportunities and place

these on the timeline. As part of this it is planned to develop a simple web page, linked to the prediction code, with a method of adding requests to the timeline. For this the prediction code will be wrapped in an ActiveX control. A planning tool will then be used by the mission planner to select requests from the payload timeline, for uploading to the spacecraft. This planning tool will incorporate the command generation software developed for ImTarget. By splitting the application in this way it means users can submit requests, knowing when there is an opportunity. This tool will be used by Reuters to submit Disaster requests for the DMC.

7. Conclusions

An innovative approach and related algorithms are developed, aiming to provide a fast way for predicting potential imaging opportunities of satellite subjecting to different camera's configuration and attitude maneuvering abilities.

A new user-friendly imaging scheduling software system has been developed to predict and schedule images on SSTL spacecraft.

It employs novel prediction routines that are faster to calculate opportunities than traditional approaches. Although implemented in the ground software, the algorithms lend themselves well to possible implementation on the spacecraft, for autonomous tasking of targets, based on Latitude and Longitude.

The ground software has been developed in a way, that is easily expandable and the way it handles commanding of the spacecraft is very generic. The system makes tasking easy and quick, and eliminates many of the potential errors, by reducing the number of user stages. By developing this approach for future missions it is hoped that requests for tasking will come direct from science users over the internet, and improve the turnaround time from request to data in the hands of the users.

Although satisfactory results are being achieved, continuing operations will be able to reduce the errors in the whole system further.

References

[1] Chu, V., Da Silva Curiel, R.A., Sun, W. & Sweeting, M. "Disaster Monitoring Constellation", *51st International Astronautical Congress*, 2-6, Oct.2000, Rio de Janeiro, Brazil, IAA-00-IAA.11.4.03

[2] Da Silva Curiel, R.A., Sun, W., Sweeting, M., Jolly, G. & Stephens P. "The 'GANDER' Mission ", *51st International Astronautical Congress*, 2-6, Oct.2000, Rio de Janeiro, Brazil, IAA-00-IAA.11.4.05

[3] Palmer, P.L. & Mai, Y. "A Fast Prediction Algorithm of Satellite Passes", *14th Annual AIAA/USU Conference on Small Satellite*, Utah, USA, August 21-24, 2000

[4] Mai, Y. & Palmer, P.L. "A Fast Algorithms for the Long Term Prediction of Satellite Imaging & Communication Opportunities", *Journal of Guidance, Control & Dynamics*, Vol.24, No.5, 2001

[5] Wu S.-F. & Palmer P.L., "Fast Prediction Algorithms of Satellite Imaging Opportunities with Canted Camera and Attitude Control", AIAA 2001-4270, *AIAA Guidance, Navigation, and Control Conference*, Montreal, Quebec, Canada, 6-9, Aug. 2001

[6] Hashida, Y. & Palmer, P.L. "Epicyclic Motion of Satellites about an Oblate Earth", Journal of Guidance, Control & Dynamics, Vol.24, No.3, 2001, pp586-596

[7] Mai, Y. & Palmer P.L. "On the Conversion of NORAD Elements to Epicycle Elements", Journal of Guidance, Control & Dynamics, Vol.24, No.2, 2001, pp406-407

[8] Hoots, F.R. & Roehrich, R.L. "Models for Propagation of NORAD Element Sets", SPACETRACK REPORT NO. 3, Aerospace Defense Center, Peterson, USA