A Simple Stochastic Approach to Small Constellation Satellite to Antenna Contact Scheduling

Robert J. Kanick\textsuperscript{1} and Jon B. Upham\textsuperscript{2}

\textit{DigitalGlobe Inc., Longmont, CO, 80302}

DigitalGlobe currently operates a constellation of three low earth orbit imaging satellites and four high-latitude relatively geographically close ground antennas. The contact scheduling of such a small but overlapping network of resources presented enough challenges as to demand automation. An internally-developed simple stochastic algorithm has proven quite successful in producing timely and efficient scheduling of these resources. This paper describes the nature and performance of this algorithm.

\textbf{Nomenclature}

\begin{itemize}
  \item DG = DigitalGlobe
  \item DFT = DigitalGlobe’s Deconfliction & Scheduling Tool
\end{itemize}

\section{I. Introduction}

DigitalGlobe (DG) currently operates a constellation of three low earth orbit imaging satellites and four ground station antennas. With the three satellites requiring downlink communications on virtually every orbit and the geographical proximity of the four ground antennas, resource-rich (surplus) and resource-poor (conflicts) scheduling choices constitute more than 40\% of the available contact periods. This presents many opportunities for scheduling situations too complex for efficient or even satisfactory manual solutions. In fact, just the approach of a single satellite and all its contingent constraints can be sufficient to present a challenge to manual scheduling. Consequently, DG internally developed and employs an automated tool to resolve conflicts (a.k.a. deconfliction) and schedule communications for its constellation.

DG’s automated tool, DFT, uses a simple stochastic algorithm to randomly search for schedules that best meet the priorities and constraints configured for various operational situations. The nature of the DG network is described to offer a sense of scale and complexity of the scheduling problems encountered. This, along with example analyses, sets the backdrop for the description and performance capabilities of the DFT algorithm.

To understand the discussions that follow, it is important to define the term “analysis” as used herein. An analysis is anytime the DFT algorithm has accumulated a set of satellites and antennas in view of each other within a given time period to the exclusion of all other resources. This will become clear when viewing the examples shown in Section III.

\section{II. The DG Network}

DG currently operates three satellites in similar polar orbits but varying altitudes. QB02 operates at 450 km, WV01 at 496 km, and WV02 at 770 km. DG operates four ground antennas, two co-located at Tromso, Norway are labeled 1NW and 2NW. One antenna at Prudhoe Bay, Alaska is labeled PB and one at Fairbanks, Alaska is labeled AK. The proximity of these antennas means that most situations bind all of the visible antennas into a single scheduling analysis. This also becomes clearer when looking at the examples in Section III.

\section{III. Example Analyses}

To give one an idea of the types of scheduling problems that are being analyzed by the algorithm, examples are presented here for analyses involving one, two and three satellites respectively and generally all of the antennas. These examples are representative of some of the more complex analyses that are encountered. When reviewing

\begin{itemize}
  \item \textsuperscript{1} Senior Software Engineer, Space Operations, DigitalGlobe Inc.
  \item \textsuperscript{2} Manager, Software and Systems Engineering, Space Operations, DigitalGlobe Inc.
\end{itemize}

American Institute of Aeronautics and Astronautics
these examples, bear in mind that various physical constraints, such as antenna turnover time, spacecraft gimbal move time, etc. must be met. As a result it will appear as though not all of the possible contact periods are used.

Fig. 1 is an example of an analysis involving only a single satellite. Note that, even for a single satellite, the solution is not trivial. This is reflected in the convergence data shown in Section V. Even cases this simple warrant the involvement of an automated solution as manual scheduling is likely to miss the optimal splitting of the contact periods given the numerous constraints and priorities involved. For example, this case factored in minimum contact times required for each antenna, gimbal maneuver time from one antenna to the next, and the relative importance of scheduling at each of the antennas (as well as others).

Fig. 2 is an example of an analysis involving two satellites. Cases such as this are already complex enough that manual scheduling is tedious at best and will always miss more efficient schedules at worst.

Fig. 3 is an example of an analysis involving three satellites. Analyses such as this are relatively infrequent, but solving them efficiently is often crucial to ensuring adequate communication time for all satellites. This example is
one of the infrequent solutions in which conflicts caused the loss of contact time for one of the satellites, QB02. Although the solution appears non-optimal, it is the best that can be done given the constraints and priorities, i.e. it was more important in this case that the contact times at antennas 1NW and 2NW be given to WV01 and WV02 respectively, leaving very little for QB02.

IV. The Algorithm

On the surface, an automated algorithm to schedule the communications for such a small constellation and network of ground antennas seemed a simple case of compiling the necessary heuristics and applying these to each collection of scheduling choices. Upon further analysis, however, it became apparent that heuristics alone yield neither the best efficiency in resource use nor a simple, maintainable automated solution. The application of arcane constraints or the stepping through the solution space became tedious and often excluded potential solutions. Randomization offers the ability to search widely in the solution space and evaluate solutions based on a highly configurable set of priorities.

DG’s satellite deconfliction and scheduling tool (DFT) is a simple stochastic search algorithm that randomly searches the solution space and evaluates/chooses schedules based on a highly configurable value/priority tree (in lieu of a value function). Flexibility is maintained by allowing the specification of direct (forced) assignments, antenna/satellite/band outages, and numerous system parameters and constraints to help guide the algorithm to preferred solutions.

The algorithm begins by gathering all of the available resources for a given analysis. This is based on temporal discreteness, i.e. what satellites and antennas are in contact with each other at any given time to the exclusion of all others. Next, given the resources available, the randomizer attempts to assign as many contacts as possible. When all resources have been assigned or discarded, a set of constraints and priorities are applied to determine the value of the solution. This process of assignment and evaluation is repeated for a configurable number of cases.

Many aspects of this process can be controlled and are exposed to operational personnel via a configuration file. Antenna priorities or availability, contact constraints such as outages or forced assignments, and even settings that can fine-tune the algorithm such as how much splitting of contacts is allowed or how many cases are attempted to find a solution.

Other than physical constraints, there are very little, if any, heuristics to guide the solutions being sought by the algorithm. This, of course, can lead to lengthy times in finding solutions as is evidenced by the discussion on analyses involving three satellites in Section V. However this must be balanced against the simplicity and maintainability of both the algorithm and the tool’s configuration file, which must be clear and concise enough to be manipulated by operational personnel.
V. DFT Performance

The challenge to a randomized algorithm is to produce reasonably optimal solutions in a reasonable timeframe. Both of these criteria are subjective to the situation and value placed on the results.

For DG, the measure of a reasonably optimal solution is often how well the needs of downlink capacity for all spacecraft are met. In this regard, a straightforward metric provides a measure of the performance of the algorithm. The metric is how much downlink time is achieved with the algorithm versus the maximum possible. The maximum possible is obtained by determining how much downlink time is possible for a single satellite passing over all antennas given all physical constraints (e.g. a satellite can only link to one antenna at a time, gimbal maneuver times, etc.). Given this metric, the algorithm is able to schedule on the order of 97.0%-97.5% of the maximum possible downlink time for each satellite. The remaining 2.5%-3.0% is due to conflicts with other satellites for the resources available. In other words, the algorithm does as well as is possible in making assignments.

The next consideration is then the timeliness of such solutions. An analysis with all three (3) satellites and all four (4) antennas available to assign can run 1000 cases in less than 30 seconds. The number of cases the algorithm takes to find its best possible solution, for all practical purposes “convergence”, is a function of how complicated the analysis is, i.e. the number of satellites. Convergence on the best solution the algorithm could find is shown in Figs. 4, 5, and 6 below for one, two, and three satellite analyses, respectively.

Regarding the use of the term convergence, note that the algorithm does not actually converge per se on a solution but rather convergence is interpreted from the quality of the solutions found. *The same number of random cases is tried regardless of analysis progress.* This is because such an algorithm could conceivably find a solution relatively quickly that is not at all well optimized. So it is important to note that what is being represented by convergence is that near-optimal, if not completely optimal, solutions are in fact being found. Thus, in the figures below, the horizontal axis displays the case number where the best solution for a group of analyses was found and that “best solution” is in fact optimal or relatively near-optimal. Of course there is often no real optimum to be found and solutions are gauged on being “good enough” given the needs of the system and/or business.

Fig. 4 shows that, for analyses with a single satellite, convergence happens very quickly—well inside of 50 cases—as one would expect for there is very little to vary and few trade-offs to consider when there is only one satellite. However, it’s apparent from this figure that solutions are not trivial and, due to constraints or other factors, some of the better solutions take a thorough search of the solution space.

![Figure 4. Number of Analyses with a single satellite as a function of case number of best solution.](image)

Figure 5 shows that, for analyses with two satellites, convergence is effectively reached by approximately 50 cases.
but sometimes as many as 500 cases. Clearly, these types of analyses are still very fast and not challengingly complex.

Figure 5. Number of Analyses with two satellites as a function of case number of best solution.

Figure 6 shows that, for analyses with three satellites, convergence is less clear as the number of cases at which the algorithm finds its best solution remains significant along the x-axis for well over 1000 cases. Nevertheless, the solutions found after only 100-200 cases are quite adequate given constraints and seldom if ever compromise on downlink time scheduled.

Figure 6. Number of Analyses with three satellites as a function of case number of best solution.

Because the algorithm employs only a minimum of heuristics, convergence in a timely manner is achieved by parallelizing analyses as well as seeding analyses with prior optimization results. Consequently, 30 days of
scheduling for a constellation of three satellites and four ground stations can be completed in as little as two minutes. Without prior optimizations taken into account, 30 days of scheduling can be completed in approximately 10-15 minutes depending on the number of cases analyzed. Future expansion of the constellation and/or number of ground stations can still be handled within these timelines with the inclusion of some additional yet simple heuristics such as a convergence metric or metrics that can measure progress to, if not achievement of, an adequate solution. Another basic heuristic is the exclusion of trials that proceed down known blind alleys.

VI. Conclusion

DFT is a simple, maintainable, highly configurable algorithm capable of deconfliction and scheduling of a small satellite-antenna network. Ultimately, the development of a stochastic approach proved remarkably simple, agile, and efficient in scheduling DG’s resources. The software can be generated robustly in perhaps three months and is quite an effective alternative to the purchase of off-the-shelf scheduling software. As business needs evolve, such in-house developed software can provide simpler expansion and agility in meeting those needs.