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Joint Intelligence Collection and Analysis Capability—Intelligence Collection—Final Report

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IMPORTANT INFORMATIVE STATEMENTS

Abstract

Under the Defence Research and Development Canada (DRDC) 05da Joint Intelligence Collection and Analysis Capability (JICAC) project, this Scientific Report proposes innovative contributions providing advanced intelligence collection tasking support to operations as part of the intelligence requirements management and collection management (IRM/CM) capability. It reports on the design of novel collection tasking optimization tools aimed at supporting the collection manager in dealing with complex tasks and collection assets. It summarizes new research and development intelligence collection concepts and automated decision support/planning capabilities to support/recommend/advise the collection manager on effective and efficient resource allocation. Focusing on the multi-satellite collection scheduling use case problem, new technology solution concepts leading to fast, automated and optimized collection tasking, providing service level improvement and enhanced timely situational awareness are briefly reported. Underlying concept novelties borrowed from artificial intelligence and operations research aim at maximizing collection value, subject to a variety of task, opportunity, resource capacity, temporal and cost constraints. The Report summarizes technical achievements describing new fast, automated and optimized collection tasking solution approaches and prototype recommenders to schedule real/virtual multi-satellite constellations. It copes with deficiencies and challenges such as myopic (single task-focused) and/or ad hoc intelligence collection tasking approaches, unsuitable centralized/decentralized open and closed-loop resource management methodology or framework to ensure static/dynamic planning or handle constraint multiplicity/diversity and uncertainty management. The Report also aims at informing Canadian Forces Intelligence Command (CFINTCOM), Director General Space (DG SPACE), Canadian Joint Operations Command (CJOC) and key military Joint Intelligence, Surveillance and Reconnaissance (JISR) stakeholders as well as the Research and Development (R&D) community on main technical findings and follow-on recommendations. It underlines the value of space-based resource management optimization to enhance situational awareness, target detection, tracking and identification through the Canadian territory, including the Arctic region.

Significance to Defence and Security

This Scientific Report presents novel collection tasking technology concepts and technical findings on the multi-satellite intelligence collection scheduling problem, applicable to space-based intelligence, surveillance and reconnaissance. This work is suitably aligned with the RADARSAT Constellation Mission (RCM) project follow-on initiatives and some Canadian Forces (CF) priorities on persistent joint intelligence, surveillance and reconnaissance in the Arctic and the North to timely propose enhanced intelligence collection tasking solution and tools. It proposes new science and technology approaches to provide near optimal intelligence collection for low-density, high-demand deployable collection assets.

Résumé

Dans le contexte du projet RDDC 05da Joint Intelligence Collection and Analysis Capability (JICAC), le présent rapport scientifique propose des contributions innovantes offrant un soutien avancé en matière de cueillette du renseignement aux opérations dans le cadre de la capacité de gestion des besoins en renseignement et de gestion de la cueillette (GBR/CM). Il rend compte de la conception de nouveaux outils d'optimisation de tâches de cueillette visant à aider le gestionnaire de cueillette à composer avec des tâches complexes et des ressources de cueillette. Il résume de nouveaux concepts de cueillette de recherche et développement et des capacités d'aide à la décision/de planification automatisées afin de soutenir/recommander/conseiller le gestionnaire de cueillette sur l'allocation efficace et efficiente des ressources. Misant sur le problème du cas d'utilisation de la planification de la cueillette multi-satellite, de nouveaux concepts de solutions technologiques menant à des tâches de cueillette rapides, automatisées et optimisées, résultant en l'amélioration du niveau de service et une meilleure connaissance de la situation sont brièvement décrits. Les nouveaux concepts sont inspirés de l'intelligence artificielle et de la recherche opérationnelle et visent à maximiser la valeur de la cueillette, sujet à une diversité de contraintes temporelles et financières et à d'autres contraintes reliées aux tâches, aux possibilités et aux capacités en matière de ressources. Le présent rapport résume les réalisations techniques décrivant de nouvelles approches de solution de cueillette rapides, automatisées et optimisées et des prototypes aviseurs pour céduler de réelles/virtuelles constellations multi-satellites. Il aborde les déficiences et les défis tels que les approches de cueillette du renseignement myope (axées sur une seule tâche à la fois) et/ou ad hoc, et une méthodologie ou un cadre de gestion des ressources en boucle ouverte et fermée centralisée/décentralisée inadéquate pour la planification statique/dynamique ou pour régir la multiplicité et la diversité de contraintes et la gestion de l'incertitude. Le rapport vise également à informer le Commandement du renseignement des Forces canadiennes (COMRENSFC), le Directeur général – Espace (DG – Espace), le Commandement des opérations interarmées du Canada (COIC), les principaux intervenants militaires dans le domaine du renseignement, de la surveillance et de la reconnaissance interarmées (JISR) ainsi que la communauté du secteur de la recherche et du développement sur les résultats les plus importants et à leur fournir des recommandations. Il souligne la valeur de l'optimisation de la gestion de ressources spatiales afin d`améliorer l`éveil situationnel, la détection, le traçage et l`identification de cibles sur le territoire canadien, y compris l'Arctique.

Importance pour la défense et la sécurité

Ce rapport présente de nouveaux concepts et résultats techniques au problème d'ordonnancement multi-satellites de cueillette du renseignement applicable au renseignement, à la surveillance et à la reconnaissance à partir de l'espace. Cette contribution est parfaitement alignée avec les initiatives de suivi du projet Mission de la Constellation RADARSAT (MCR) et certaines des priorités des Forces Canadiennes telles la persistance du renseigne ment, la surveillance et la reconnaissance dans l'Arctique et le Nord et vise à proposer une solution améliorée et des outils de planification de cueillette du renseignement. Il propose de nouvelles approches en matière de science et de technologie visant une cueillette du renseignement quasi optimale pour des ressources déployables de faible densité, lesquelles sont en forte demande.

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1 Introduction

Cost-effective space-based intelligence collection tasking targeted at suitable intelligence, surveillance and reconnaissance (ISR) application domains is essential to the development of a suitable defence intelligence requirements management and collection management (IRM/CM) capability. Accordingly, collection management and collection tasking in particular, is paramount to maintaining accurate, timely, and persistent situational awareness of Canada's territory, air and maritime domains. Typical collection management requirements include adaptive and responsive collection when operating under limited resources (CFINTCOM); collection tasking; plan execution; sensor mix optimization; support dynamic re-tasking of Joint ISR (JISR) assets (CJOC); and real-time collection planning as well as efficient sensor cueing and tipping (DG SPACE), to name a few. Ultimately aimed at efficiently bridging the gap between information need and information-gathering, near-optimal resource management is primarily motivated by staff shortage, limited collection tasking automation, cost-effectiveness, resource limitations, and low-density high-demand collection asset (satellite) evolving in a time-constrained uncertain environment. Spaced-based imagery intelligence (IMINT) through the multi-satellite collection scheduling problem (*m*-SatCSP) for Arctic intelligence and surveillance represents a typical use case of interest.

Proposed solutions to deal with intelligence collection tasking deficiencies and challenges [1] are numerous. A general high-level overview of recent open literature contributions on collection tasking, and multi-satellite image acquisition scheduling in particular, is reported in "Collection Planning and Scheduling for Multiple Heterogeneous Satellite Missions: Survey, Optimization Problem, and Mathematical Programming Formulation" [2] and "QUEST—A New Quadratic Decision Model for the Multi-Satellite Scheduling Problem Computers and Operations Research" [3]. A brief summary of the main limitations of the proposed approach are highlighted below. The reader is referred to the latter publications [2] [3] for more explicit details. Based upon a low-density high-demand collection assets premise, the general problem is computationally hard. Most research contributions are mainly restricted to homogeneous satellites and single constellation settings, deal predominantly with simple target observation point target ("spot" areas) tasks, and propose new task clustering and preprocessing strategies to mitigate computational complexity. Reported work mostly overlooks large area coverage intricacies, complex task structure, joint value task composition, uncertainty on observation outcome and imaging opportunity quality, as well as common operational constraints. Such constraints include minimal task coverage thresholds, mutual task exclusion, task precedence and imaging costs. Current collection asset tasking solutions mostly provide near-sighted heuristic-based policies to plan or allocate collectors to mission tasks. In practice, best resources are often myopically recommended or locally selected for a given task overlooking other constraints (e.g., time windows and imaging opportunities for servicing other collection requests), global objectives pursued and ongoing partial schedule solution quality. Accordingly, ISR resource allocation and dynamic retasking is traditionally ad hoc in the sense that they are single task-focused, rather than adopting a more holistic mission view paying attention to the overall tasks and better exploit alternative opportunities to meet more efficiently global collection requests as a whole. Proposed basic collection tasking partial solutions do not provide a sound resource management framework to ensure adaptive dynamic planning or to handle constraint multiplicity/diversity and uncertainty management. They also fail to demonstrate valuable distributed planning and fusion synergy or integration while presenting little guidance to support reconfigurable sensor networks. Gap reduction between sense-making or high-level information fusion, and resource allocation (RA) tasks on the one hand, and, between planning (tasking) and execution (collection) monitoring on the other, remain elusive.

This work presents new research and development intelligence collection concepts and automated decision support/planning capabilities to support/recommend/advise the collection manager on effective and efficient resource allocation. It is aimed at developing automated advisory scheduling components and proof-of-concept prototypes for effective collection tasking. Focusing on multi-satellite image acquisition (IMINT) scheduling, new technology solution concepts leading to fast, automated and optimized collection tasking providing service level improvement and enhanced timely situational awareness are introduced. The envisioned problem includes many new additional features and refined elements that primarily remain overlooked or ignored in open literature. Assuming a *m*-SatCSP in conditions of low-density, high-demand collection assets, new features include collection asset diversity and agility, task abstraction, a more inclusive objective and more constraint diversity. The revisited formulation involves abstract intelligence gathering task generalizing single target areas (spot) focus to include large area coverage explicitly while considering multiple or virtual heterogeneous satellite constellations departing from traditional homogeneous settings. The proposed approach distances itself from the old-fashioned view in many respects, considering a weighted task decomposition structure combining composite or abstract requests capturing new spatial and temporal dependencies, reflecting more realistic mission complexity and relaxing mutual independence and separability assumptions. It captures notions of imaging quality, partial task execution and probability of success moving away from unrealistic assumptions on orderly action execution or deterministic outcome. The approach also revisits the concept of task priority utilization. Accordingly, priority is used as a conflict resolution mechanism, rather than a biased myopic priority-based policy imposing arbitrarily task partial ordering to manage high complexity demand. The envisioned problem objective intends to capture a task-specific measure of performance beyond usual area coverage, introducing quality of collection which accounts for detection success, tracking quality, and identification/recognition uncertainty to enhance collected information value. Based on a problem statement recently proposed to contextualize the *m*-SatCSP [3], mapping intelligence requests to collection asset imaging opportunities to maximize collection value, this work briefly extends the standard deterministic problem decision model, using a formal mixed-integer quadratic programming optimization problem formulation [5]. Targeted to space-based ISR application domains, the new optimization model reduces computational complexity, making possible the utilization of exact problem-solving methods in some cases, while providing a bound on the optimal solution. On top of traditional feature constraints largely reported in open literature, the promoted model introduces additional specifications, such as suitable task coverage thresholds, optional task mutual exclusion, task precedence, joint value task composition, imaging/service time windows, and thermal constraints over individual and average orbits. Main contributions and novelties in various static and dynamic settings for centralized and decentralized decision-making contexts are reported. Innovative models, solvers and proof-of-concept prototypes (recommender) explicitly developed to support collection tasking are briefly described.

This Scientific Report summarizes technical achievements describing new fast, automated and optimized collection tasking (service level improvement, enhanced situational awareness) solution approaches and prototype recommenders to schedule multi-satellite real/virtual constellations. It is also aimed at informing CFINTCOM, DG SPACE and CJOC military organizations on the main findings and identify most promising collection management performance requirements, technology and tools, prone to have a potential impact on ongoing major military initiatives. This work has been conducted under the DRDC Joint Force Development (JFD) 05da Joint Intelligence Collection and Analysis Capability (JICAC) project between December 2015 and March 2020.

The Report is outlined as follows. Section 2 briefly introduces the *m*-SatCSP problem statement. It describes the basic problem features and highlights open-loop and closed-loop settings as well as centralized and decentralized decision-making contexts. Respective open-loop (static) and closed-loop (dynamic) proposed contributions are summarized in Section 3 and 4 respectively. The developed concepts, model features, algorithms or solvers and main results are briefly introduced and discussed. Section 5 presents the proof-of-concept collection tasking prototypes developed explicitly under JICAC to examine static/dynamic problem settings. Core contributions, findings and their potential impact are then summarized in Section 6. Finally, recommendations are formulated in Section 7. Some directions for further technology solution exploitation and future work extensions are suggested.

2 Problem Statement—Multi-Satellite Collection Scheduling

Multi-satellite collection scheduling may be defined using open-loop or closed-loop decision models respectively. An open-loop model involves a single episode ignoring explicit observation feedback, whereas a closed-loop formulation sequentially exploits open-loop decision models over multiple episodes in a time-varying uncertain environment, taking explicitly into account feedback information (e.g., observation outcome, failed and new tasks) to ensure dynamic collection re-tasking. In either case, decision-making may be centralized or decentralized.

2.1 Open-Loop

2.1.1 Centralized

The open-loop collection problem focuses on low-density high-demand assets and involves a single episode overlooking explicit information feedback in the decision model. Focusing on imagery collection (image acquisition) scheduling, the *m*-SatCSP can be stated as follows: Given a set of information requests (areas of interest to be observed) properly translated in weighted tasks, a set of heterogeneous collection assets and supporting resources (e.g., ground stations), a collection tasking objective, a set of constraints (e.g., mission, task, operational, collector, supporting resource, communication, capacity, temporal and cost), the problem consists in allocating collection assets (owned by single/multiple stakeholders) to imaging observation task opportunities over a predetermined time horizon to optimize single or multiple objectives. A typical objective consists in maximizing the value of information (collection value). Requests are assumed to originate from requests for information, priority intelligence requirements derived from commander's critical information requirements, and prior situation knowledge (e.g., ISR picture). These are conveyed through an existing collection management process and supporting tool.

Problem description may be briefly summarized as follows:

- Input: Requests/orders, goal/task structure, collection assets (satellites, near polar orbits), time horizon (number of orbits/passes/revolutions);
- Goal: Allocate resources to maximize collection value (serviced task value) utility function;
- Task:
  - Preprocessing: Observation request area subdivision in strips;
  - Specifications: Target (spot)/region (polygon area); area definition along azimuthal and elevation coordinates;
  - Requirements including NIIRS/resolution (waveform/beam—predefined tasks and satellite combinations/parameters); mono/stereo (SAR/electro-optic (EO) sensor);
- Collection assets: Heterogeneous collection platforms and supporting resource (e.g., ground station communication asset);
- Imaging opportunity calculation (based on satellite propagation model);

- Constraints: Task visibility/precedence/priority, mandatory visits, minimal coverage, temporal: set-up/service and imaging duty cycle, time windows, conflicting opportunity transition, resource capacity: Energy budget, on-board storage, communication, dissemination, mission single and cumulative maximum imaging cost, an imaging observation cannot be interrupted;
- Output: Collection schedule (image acquisitions/observations).

A detailed problem specification may be found in "Multi-Satellite Intelligence Collection Scheduling—Problem Statement" [3].

2.1.2 Decentralized

The decentralized *m*-SatCSP expands the centralized problem version involving a single agent (e.g., a stakeholder) supervising collection assets, considering multiple decision-makers individually controlling their own assets and resources. This is exemplified by ISR individual satellite constellation owners and/or service providers (e.g., organizations, nations) sharing common and individual mission objectives and teaming together by coordinating their respective collection plans. The novelty in the decentralized planning setting is that individual plan interdependencies are mitigated by a coordination mechanism. Coordination may be either centralized or decentralized.

2.2 Closed-Loop

The closed-loop *m*-SatCSP generalizes the single episode open-loop formulation considering multiple episodes in time-varying uncertain environment taking into account feedback information (e.g., observation outcome, failed and new tasks) to ensure dynamic collection re-tasking. A pure closed-loop problem formulation explicitly incorporates information feedback in the decision model accounting for any built-in contingencies (stochastic exogenous events) providing a policy solution, mapping a world state to a collection action. In contrast an alternate closed-loop scheme which relies on an "open-loop with feedback" decision model, repeatedly solves a new episodic (static) open-loop optimization problem conditioned by latest information feedback (observation outcome, new tasks) and acquisition commitments, continually expanding/repairing the best partial collection path solution computed so far. Accounting for explicit feedback information, the closed-loop setting includes image downlink scheduling as well. In order to keep the problem manageable, downlink assumes a prior communication policy. A typical communication policy consists in downloading past image acquisitions first, before initiating a new satellite collection scheduling cycle. Given project resource and time constraints, research efforts have been limited to a centralized decision scheme.

3 Open-Loop Multi-Satellite Collection Scheduling—Concepts, Models, Algorithms

Open-loop solutions developed and investigated for centralized and decentralized decision schemes are respectively described in this section.

3.1 Centralized Approach

Based on the problem statement introduced in "Multi-Satellite Intelligence Collection Scheduling—Problem Statement" [3], deterministic decision models have been developed for an open-loop, centralized, multi-satellite (Earth Observation) intelligence collection tasking (image acquisition) problem, proposing a baseline [5] and an extended formulation [3]. The extended decision model combines a classical coarse-grained model component generally designed for complex tasks in which limited complex task plans must be implicitly precomputed, to a fine-grained model component focusing on non-complex tasks (no predetermined task plans available) such as area target coverage further expanding exploration of the search space for better solutions. The fine-grained component models task area coverage explicitly rather than relying on complex area precomputations, generalizing point target tasks, introduces composite request abstracting primitive request definition and convenient to combine multiple related tasks whenever required. Accordingly, the decision model restricts limited number of costly plan precomputations to a small number of highly complex tasks while expanding search over a larger solution space for alternate non-complex tasks aiming to improve solution quality. It is worth mentioning though, that in some cases, certain coverage tasks (e.g., large area coverage) may still be assumed complex as a composite plan must be built from a large number of subplan combinations (e.g., large area coverage task). It further extends the basic concept of constellation traditionally formed of homogeneous trailing satellites to any heterogeneous satellite constellation configuration. Moving from a disjoint to an overlapping strip task decomposition scheme, it allows properly and efficiently handling area task coverage in a single model.

Largely limited to single constellation and homogeneous satellite collection scheduling problems for convenience purposes, currently known model formulations from the open literature [6–10] fail to explicitly capture coverage contributions involving multiple intersecting areas, while being computationally prohibitive to generate provably optimal solutions. As a result, problem-solving has primarily been restricted to the use of heuristic methods and metaheuristic techniques. In contrast to exclusively develop approximate problem-solving techniques to an exact hard problem model, the development of an approximate model using exact techniques can be alternately contemplated as well. Featuring heterogeneous satellites and constellations, the proposed integer programming optimization model includes a composite coverage approximation function combining arbitrarily overlapping strip areas (imaging opportunities) emerging from various sensor geometry. Accordingly, the proposed reformulation permits to capture any overlapping imaging opportunity strip area configurations defining a target/task for multiple concurring satellite opportunities, rather than exclusively relying on disjoint (parallel) imaging opportunity areas target/task decomposition requirements which negatively impact solution quality by deliberately overlooking alternate potential overlapping opportunities. In its simplest form, area coverage second-order approximation consists in subtracting the sum of opportunity areas covered from the sum of mutually intersecting areas over all covered opportunity area pair combinations. This approach tends to naturally penalize solutions having significant area intersections among selected opportunities, alternately encouraging opportunity composition presenting minimal overall intersecting areas in covering the targeted area of interest.

The proposed mixed-integer quadratic collection scheduling (tasking) network flow problem reformulation extends classical models while reducing combinatorial complexity. The model presents suitable objective function and constraint convexity properties, making well-known powerful optimization technology at our disposal to optimally solve large problems or compute optimality gap. The approach assumes a predefined mission decomposition scheme reflecting a hierarchical goal structure. At each level, a nominal value reflecting priority on information need is attached to a goal node. Nominal value apportionment is achieved from the top level goal down to the task level. Lower level goals correspond to collection tasks. Multiple objectives are currently represented via a main objective along with subobjectives alternatively described as constraints. The decision model introduces the notion of quality of information/service coupled to partial task completion/satisfaction, heterogeneous satellites from multiple constellations, overlapping imaging opportunities (substituting fixed strip pattern-driven for opportunity-driven task area decomposition), captures primitive and compound tasks while incorporating multiple task coverage requirements as a work unit. The network flow formulation alternately makes use of a collection graph to conveniently capture feasible opportunity transition and facilitate constraint expressivity, implicitly encoding conflicting opportunity or certain time constraints. The proposed decision model presents a variety of new constraints, namely, task requirements (mandatory, precedence, mutual exclusion), opportunity transition (conflicting opportunity over consecutive orbits which improperly remain largely ignored in literature), temporal (time windows to accommodate agile satellite), satellite utilization/imagery budget or cost, task, resource (primarily collection assets), satellite thermal capacity (average over multiple orbits). Finally, contrarily to most state-of-the-art reported work, the new problem model formulation provides a solution quality (collection value) upper bound which can be rapidly computed from the relaxed problem decision model (decision variable integrity relaxation), presenting an objective measure to compute optimality gap to properly compare relative performance from alternate techniques.

3.1.1 Collection Tasking Mathematical Model

A mixed-integer quadratically-constrained problem formulation for the deterministic open-loop decision problem is proposed [5]. It revisits standard nonlinear collection tasking problem modeling resulting in a mixed-integer quadratic program (MIQP). The MIQP model exploits an acceptable second or third-order approximation to estimate coverage calculations while reducing undesirable area opportunity intersections or overlap leaning towards unnecessarily increasing redundancies and cost. The formulation relies on a directed acyclic graph representation to depict possible imaging observation moves for each satellite revolution and, a mathematical model to explicitly capture the decision problem objective and constraints. The graph representation proves particularly convenient to easily specify problem constraints in the decision model.

Exploiting the above graph representation, definitions and notations, a preliminary mixed-integer quadratic program (MIQP) formulation has been proposed. The objective consists in maximizing expected collection value subject to various constraint sets:

TASK:

- Mandatory task visits;
- Minimal area coverage (proportion: %);

- Precedence task constraints (e.g., detection/confirmation/tracking/identification);
- Mutually exclusive tasks (e.g., competing requests);
- Complex task service (e.g., large area coverage request, stereo request);
- Compound request imposing all task components to be serviced as a unit;

RESOURCE CAPACITY:

- Image acquisition cost (over particular task or a mission);
- On-board memory storage capacity;

RESOURCE CAPACITY per ORBIT:

- Visibility (task visibility over a given satellite orbit);
- Energy budget (imaging, imaging opportunity transition energy requirements);
- Maximum number of sensor openings by orbit (orbit capacity);

TEMPORAL:

- Time window (request and task servicing/deadlines, imaging opportunity time interval);
- Transition (intra and inter-orbit consecutive imaging opportunity);
- Image acquisition cost (over particular task or a mission);
- On-board memory storage capacity;
- Imaging duty cycle imposed by thermal constraints (maximum imaging time per orbit, and on average over multiple consecutive orbits).

A formal problem decision model formulation may be found in "Multi-Satellite Intelligence Collection Scheduling—Decision Model" [5] and "QUEST—A New Quadratic Decision Model for the Multi-Satellite Scheduling Problem Computers and Operations Research" [3].

3.1.2 Problem-Solving

Proposed scheduling algorithms encapsulated in problem solvers are inspired from operations research and artificial intelligence. They are based on the development and reutilization of heuristics, metaheuristics and soft computing procedures (e.g., genetic), as well as exact mixed-integer programming optimization methods or a combination of them. Problem-solving techniques reutilization (open-loop with feedback) from well-known related problems (e.g., vehicle routing problem with time windows, constrained longest path problems and variants) are also adapted and/or exploited. Baseline comparison with ongoing user-defined and naïve scheduling heuristics have been highlighted. A suite of new open-loop centralized algorithms have been implemented as solvers, ranging from a fast human-like myopic technique (MYopic Planning-based Image aCquisition heuristiC [MY_PICC] [11]) and state-of-the-art genetic-based metaheuristics (Hybrid Genetic Algorithm [HGA] [12], Genetic Algorithm-based collecTion scHedulER [GATHER] [11]) to an exact method solving an approximate decision model (QUEST [3]) and, a two-step decomposition heuristic procedure exploiting exact methods (Mixed/Multi Overlapping Sub-Area composItion Coverage [MOSAIC] [13]).

MY_PICC: The MYopic Planning-based Image aCquisition heuristiC (MY_PICC) [11] is a myopic heuristic naively mimicking a human-like strategy. The myopic heuristic consists in moving along orbital collection graphs in parallel, and to constructively schedule the next image acquisition, awarding the collection presenting the highest payoff rate (per time units) within the vicinity of the latest observation of a current path solution. The payoff rate refers to the ratio of expected collection gain over combined delays imposed by satellite travel, feasible transition and imaging durations respectively. Earliest start time occurrence breaks ties.

HGA: The *H*ybrid *G*enetic *A*lgorithm (HGA) [12] is a vehicle routing with time windows (VRPTW)-based method designed to tackle the single objective static *m*-SatCSP. The latter presents similarity with well-known operations research capacitated VRPTW problem variants. In this setting, the *m*-SatCSP is reduced to a constrained VRPTW in which satellites represent vehicles having limited visibility on tasks associated with customers, imaging observations are mapped to servicing customers, and orbits correspond to periodic vehicle tours (routes), subject to a variety of task and resource capacity constraints (e.g., energy budget, on-board memory storage, communication bandwidth). The advocated approach combines and adapts well-known routing heuristics knowledge with standard genetic operator principles to efficiently explore promising search regions, manage constraint handling and improve solution quality. The hybrid strategy co-evolves two populations of solution plan individuals, maximizing expected collection value while concurrently densifying collection paths to minimize orbit demand.

GATHER: The Genetic Algorithm-based collecTion scHedulER (GATHER) [11] evolves a mixed population of feasible/unfeasible solution individuals based on natural selection to maximize expected collection value. The advocated hybrid genetic algorithm explicitly takes advantage of collection graphs reflecting problem structure in representing feasible imaging opportunity transitions, to better manage temporal constraint handling during crossover and mutation operations. A low-cost task scheduling heuristic embedded in genetic operators, further provides directed search and speed-up, generating feasible high-quality solutions. The artificial intelligence bio-inspired technique is an anytime method, scalable, and provides multiple solutions at once. A multi-objective version (Multi-Objective Genetic Algorithm-based collecTion scHedulER [MO-GATHER]) has been developed as well.

QUEST: The *QU*adratically constrain*E*d program *S*olver *T*echnology (QUEST) [3] generalizes mainstream approaches currently available, often limited to a simple trailing satellite constellation and disregarding or oversimplifying footprint coverage intricacies. It departs from traditionally known and intractable approaches, relying on a new coverage approximation to deal with partial area coverage superposition conferring the objective function and constraints of the optimization problem with desirable convexity property. This enables exploitation of available and powerful exact problem-solving techniques. QUEST is based on network flow optimization using mathematical programming. Unlike previous methods, it relies on a sound alternative approximate objective function and, the exploitation of exact problem-solving techniques. Derived from domain knowledge and problem structure considerations, QUEST generalizes problem modeling to successfully handle virtual constellations, avoiding unsuitable utilization of traditional area coverage decomposition schemes. The proposed decision model concurrently captures coverage approximation, imaging success uncertainty and quality for a variety of tasks subject to a variety of novel task (e.g., precedence, mutual exclusion), opportunity, and resource capacity, temporal and cost constraints. The approach also provably provides an acceptable upper bound on collection value, a significant step forward in objectively assessing delivered solution quality. A QUEST variant alternatively relying on "delayed reward" to bridge promising search regions on move selection, further shows optimality gap reduction and provides additional speedup. Computational results prove QUEST to be cost-effective and to outperform some recent baseline methods derived from best-known *m*-SatSP procedures. It comparatively demonstrates measurable collection and run-time gains, and provides a tight upper bound on the optimal solution of hard problems. Performance results comparing My_PICC, GATHER and QUEST solvers are reported and discussed in "Multi-Satellite Collection Scheduling" [14]. QUEST is the best known state-of-the-art approach for the static *m*-SatCSP.

MOSAIC: The *M*ixed/Multi *O*verlapping *S*ub-*A*rea compos*I*tion *C*overage (MOSAIC) [13] problem-solver has been alternatively designed to specifically address satellite imaging acquisitions for large area coverage problems. Demand for large area coverage is pervasive over a variety of military and emergency response application domains. The basic approach combines a single objective multi-satellite collection scheduling decision model and an innovative two-stage algorithm to solve the large area coverage problem. It aims at maximizing collection value defined over the quality of individual image acquisitions weighted by their corresponding relative swath coverage, while minimizing area overlap. The underlying MOSAIC algorithm first maximizes collection value using mutually non-overlapping swaths and then, fills remaining gaps while minimizing overlap. The algorithm initially partitions each imaging opportunity swath segment in sub-opportunities (time subintervals) forming contiguous subareas in order to reduce mutual overlaps. Following the two-stage procedure, it then recombines a mixture of segmented swath elements to near-optimally maximize collection value in covering the original large area. The resulting solution is a mosaic of swath subarea segments. A computational experiment conducted on the basic large area coverage maximization problem proves the value and quality of the approach exhibiting small optimality gap.

The main overall technical findings resulting from the investigated problem solving technologies described above may be summarized as follows:

- Situational Awareness enhancement; quantitative collection gain (value); Tasking, Collection, Process, Exploitation and Dissemination (TCPED) process speedup; shorten tasking cycle;
- Service level improvement: 16-30% gain in differential relative collection value; lead time reduction, better time allocation;
- Optimal three-satellite trailing constellation problem solution;
- Upper bound on best solution quality, and run-time reduction;
- Cost-savings (unnecessary delayed collection, opportunistic collection);
- Service provider: Major operator's profit gains.

A new concept to tightly integrate high-level information fusion and collection tasking and further bridge the gap between information need and information-gathering has also been proposed. It combines discrete-event simulation, deep neural networks, knowledge-based identification and evolutionary approach to solve multi-asset collection/image acquisition scheduling in a surveillance context [15]. From an extended decision model incorporating coverage, tracking and identification tasks, it generalizes a graph-based hybrid genetic algorithm used for the *m*-SatCSP assuming heterogeneous collection asset/vehicles such as air and ground-based vehicles subject to a mixture of capacity constraints. The framework relies on plan execution simulation and neural networks to predict track trajectories target behaviours as well as a predefined knowledge-based approach to estimate target identification. Respective output are then used to determine tracking and identification task performance parameters to qualify related collection task plans in the decision model.

3.2 Decentralized Approach

Decision models have been alternatively developed for the open-loop, decentralized/distributed, multi-satellite intelligence collection scheduling problem (Dis *m*-SatCSP). The distributed decision-making approaches rely on centralized and decentralized plan coordination respectively, involving multiple decision-makers, coupled to decentralized plan execution. The problem may be stated as follows. Given a set of N surveillance assets owned and managed by a set of M independent sub-planners ($M < N$), a set of task requests and a set of Collection Opportunities, assign tasks to sub-planners' assets to optimize multiple conflicting decision objectives (e.g., maximize the overall collection value and minimizing the total mission cost).

The decentralized multi-satellite scheduling problem setting comprises multiple stakeholders having control on their own resources to be coordinated in a time-constrained uncertain environment. Aimed at maximizing global (system-wide) and local collection value objectives, satellite platform agents are assumed to have sufficient on-board processing and decision-making capability. Agent's attitude may be defined over a mixed spectrum of cooperative and competitive goal-driven behaviours. Two novel collection tasking centralized and decentralized coordination approaches relying on market-based and cooperative co-evolution mechanisms are respectively described.

3.2.1 Centralized Coordination

In the centralized coordination setting, a market-based collection tasking approach is proposed [16]. A coordination mediator (CoM) receives system-wide (global) task requests and dispatches them to multiple independent sub-planners, each of which owns a set of collection assets. Sub-planners first solve the "bidding problem:" They autonomously and independently build best local collection plans and schedules combining a mixture of global and local tasks and submit their bids (collection asset opportunity-task pairings and cost) back to the CoM. The CoM uses in turn a market-based (single item bid auction mechanism) decentralized collection tasking approach, to generate the joint collection tasking solution. Accordingly, embodying an auctioneer, the CoM solves the "winning determination problem," selecting subplanners' bids having best system-wide expected collection value (global benefit) one at a time. Selected task plans are then forwarded to all sub-planners and eventually executed by the surveillance assets they operate. A variant supporting multiple bids (alternative collection plans) by subplanners coupled to an auctioneer resorting to a genetic algorithm to search over best feasible collection plan combinations has also been proposed [17].

The CoM described by Abielmona et al. [16] operates under the following assumptions:

- CoM knows which assets are owned/managed by each sub-planner and their capabilities;
- CoM knows the set of local task requests received by the sub-planners;
- CoM knows the planning periods of the sub-planners' assets;
- CoM does not know the optimization criteria used by sub-planners to schedule their assets and cannot force a sub-planner to accept an assigned system-wide task requests. However, we assume the notion of "collection value" to define a common measure to characterize bids on a compatible scale;
- Sub-planners inform CoM about their schedules once they have done so.

The CoM relies on a multi-objective evolutionary algorithm exploiting system-wide solution dominance (Pareto front) reflecting the trade-off between two or more conflicting objectives (e.g., overall profit or collection value, and total cost) to qualify collection asset opportunity-task pairings and use an auction mechanism to ultimately assign tasks to the best sub-planners. In counterpart, sub-planners use local single-objective asset scheduling optimizers (unknown to the CoM). Each sub-planner may choose to optimize a different decision objective. The CoM utility of a collection opportunity is a function of the conflict and the resource consumption indicators for that observation opportunity.

The proposed coordination framework shows appealing properties:

- It may integrate heterogeneous assets into a loosely coupled surveillance system. Unlike traditional architectures that have no coordination or organize all assets in a centralized way, this architecture realizes coordination through interaction and communication among sub-planners. This architecture is feasible and consistent with the fact that different assets belong to independent sub-planners.
- It is modular and scalable. It allows for the addition, removal, and modification of sub-planners and assets without breaking down the overall system. In addition, this architecture is convenient for integrating legacy sub-planners and assets with new ones.
- The coordination mediator possesses a global view of the overall system and rationally allocates observation tasks to different sub-planners. This ultimately improves schedule solution quality and coordination efficiency.
- It is robust and fault-tolerant. Each sub-planner is proactive, reactive, and can decide according to internal and external environments. This feature enables sub-planners to detect and recover from failures automatically.

3.2.2 Distributed Coordination

A distributed coordination approach has been alternatively developed when a centralized coordination is either unsuitable or not feasible as often dictated by organizational, environmental or physical constraints, highlighting dissimilar goals, resource ownership diversity or self-interested agent behaviours. Accordingly, a cooperative coevolution approach [17] is proposed. It consists in learning feasible multi-agent collection plan coordination through coevolution.

In cooperative coevolution, the problem is first decomposed into several subproblems that can be optimized concurrently. For each subproblem, a corresponding subpopulation of collection path solution individuals is instantiated. In each iteration, the subpopulations are simultaneously evolved from one generation to the next. Offspring are generated through recombination and mutation genetic operators. A child collection path solution, which represents a partial solution to the overall problem, is evaluated by combining it with last generation best solutions from respective coevolving subpopulations, while accounting for constraint violations. Child performance evaluation is naturally mapped to individual fitness. Individual propensity for reproduction is proportional to its fitness value. On generation completion, the worst (lowest quality) solution individuals are rejected, restoring each subpopulation to their original size. On a new generation, subpopulations mutually share with one another their best individual (highest collection value), progressively reinforcing coevolution toward a global high-quality solution. The process continues until a stopping condition is met, namely, a maximum number of cycles or a minimal performance gain threshold. In the current distributed setting, the problem is decomposed into many satellite scheduling subproblems, one per collection asset. A subpopulations is evolved using the GATHER algorithm exposed above. The initial population is generated by randomly initializing the members of the subpopulations. More details may be found in “Distributed Satellite Collection Scheduling Optimization using Cooperative Coevolution and Market-Based Techniques” [17].

4 Closed-Loop Multi-Satellite Collection Scheduling—Concepts, Models, Algorithms

Reported closed-loop multi-satellite scheduling methods for Earth observations show many limitations when operating in time-varying uncertain environment (e.g., dynamic task demand, observation outcomes, resource failures, task duration). Despite a large body of research, advocated real-time dynamic scheduling approaches are often myopic, uninterruptible or are performed offline, occur on arbitrarily predetermined time periods, assume negligible run time or improperly account for the passage of time during planning, coming short to demonstrate anytime behaviour [18]. Proposed work contributions generally assume that world state remains unchanged while constructing the solution schedule/plan. This particularly prevails for two-stage myopic approaches relying on initial plan/schedule generation and dynamic repair. As a result, possible computational opportunities and events that may impact solution quality/feasibility or key real-time requirements such as responsiveness, timeliness and graceful adaptation are overlooked. In this section, three different dynamic problem-solving approaches investigated to handle the closed-loop *m*-SatCSP are briefly presented.

Dynamic QUadratically constrainEd program Solver Technology (DynaQUEST): A novel open-loop with feedback approach to solving the dynamic multi-satellite scheduling problem has been developed. The open-loop with feedback DynaQUEST solution [18] includes an event-driven controller monitoring dynamic situation evolution while supervising a coevolving episodic scheduling problem solver based on the QUEST solution introduced in Section 3.1.2. Reactive to real-time and delayed information feedback, the controller timely enables the problem-solver to stay responsive, interruptible and adaptive, taking advantage of emerging opportunities to timely improve solution quality. The problem-solver continually solves a new static problem shaped by dynamic changes and constrained by current resource commitments to adaptively expand the emergent solution. Problem model formulation is based on network flow optimization using quadratic mixed-integer programming. Departing from mainstream approaches widely promoting an exact objective function coupled with a heuristic problem-solving method, the proposed approach alternatively combines an approximate objective function and an exact algorithm. The approach embraces an extended time horizon relaxing myopic planning. Computational results prove the approach to be cost-effective and to outperform alternate baseline heuristics.

Mixed Open-and-Closed Loop Satellite Task Planning: A new closed-loop approach mixing ground-based open-loop satellite planning and on-board satellite closed-loop formulations has been developed [19]. As optimal closed-loop formulation may not satisfactorily take on medium or large scale problems in real-time [20] [21], a mixed open-and-closed loop algorithm is advocated taking advantage of open- and closed-loop formulations while managing uncertainty to further reduce latency and spoiled image acquisitions. Problem decomposition involves a ground segment (ground station) relying on an open-loop (with feedback) centralized collection tasking static decision model defined over a large time horizon, feeding a space segment (satellite platforms) resorting to a closed-loop model formulation over a short time horizon to support local real-time on-board plan adaptations by individual satellites. The ground segment periodically provides the space segment with a revisited long term collection tasking plan to be locally adapted, by respective satellite platforms, over a time interval separating two consecutive communication episodes with the ground station. The combined approach relies on large uncertainty level coupled to considerable processing capability anticipated at the ground level, and limited uncertainty paired to reduced processing capability generally assumed at the space level. The open-loop ground decision model is handled using mathematical programming whereas the dynamic programming closed-loop formulation (Markov decision process) is solved using a value iteration procedure.

Deep Collection Learning in Uncertain Environment (Deep CLUE): Recent progress and reported success in deep reinforcement learning (DRL) revived interest for possible applicability/suitability of the approach to solve computationally hard sequential decision planning and discrete optimization problems and the development of feasible practical solutions. The main idea is to combine an offline learning phase exploiting problem features and structure to a fast on-line planning phase. A deep neural network is first trained to learn an efficient scheduling heuristic over a large family of relevant data problem instances to determine sequence of high-quality moves, and is then exploited in near real-time to recommend a timely response to a specific problem. A preliminary investigation has been initiated to explore DRL problem-solving techniques to solve a centralized multi-satellite image acquisition scheduling problem [22]. The challenge consists in learning a suitable representation and, a collection path planning near-optimal policy (heuristic) prescribing the best information-gathering/imaging action to maximize overall collection value given the current state of the world. Accordingly, the algorithm learns a heuristic that selects the next best imaging task opportunity given the current problem and partial solution, avoiding any explicit search. Ongoing concept exploration relies on adaptations of deep graph-based Q-learning, actor-critic networks and attention mechanism paradigms using convolution and recurrent neural network architectures. Although preliminary results in learning a collection satellite scheduling heuristic still fail to outperform baseline domain specific methods, the trained system might be fast enough to potentially generate decisions in near real-time. Hybrid DRL and operations research methods combination represents an alternate research direction to further improve collection performance.

5 Proof-of-Concept Decision Support Prototypes

This section presents the most significant proof-of-concept collection tasking prototypes explicitly developed under the JICAC project to investigate key static and dynamic problem settings. They represent coevolving/complementary decision support technology components of the JICAC solution ecosystem.

5.1 ***D**eployable **I**ntelligence **S**ource **C**ollection **V**alue optimiz**ER** (DISCOVER)*

DISCOVER is the *D*eployable *I*ntelligence *S*ource *C*ollection *V*alue optimiz*ER*, DRDC's collection management proof-of-concept prototype developed under the DRDC 05da JICAC project. DISCOVER has Technology Readiness Level (TRL) 1. It is an automated decision support/planning capability aimed at supporting, recommending or advising a collection manager on effective and efficient resource allocation to maintain persistent situational awareness. The initial DISCOVER proof-of-concept prototype exploits key Commercial Satellite Imagery Acquisition Planning System (CSIAPS) [23] components, namely, collection opportunity generation, sensor-task matchmaking and plan evaluation respectively, and extends its myopic planning capability focusing on global multi-satellite collection scheduling optimization [5] concurrently considering multiple tasks and collection assets (e.g., a virtual satellite constellation) at once. Given a set of information requests (areas of interest to be observed) properly translated into weighted tasks, the single-episode (static) multi-satellite scheduling problem supporting information collection consists in allocating collection assets (satellites) to observation tasks (imaging opportunities) over a predetermined time horizon to optimize single or multiple objectives (e.g., collection value maximization, task throughput and financial cost minimization), subject to a variety of constraints. Typical constraints may relate to:

- Mission, task and related dependencies;
- Operational setting including collector diversity, supporting resource features, and on-board resource capacity (e.g., energy, memory, communication);
- Temporal conditions (e.g., imaging opportunity transition, imaging and task completion time windows);
- Itinerary contingencies (e.g., duty cycle referring to maximum orbital cumulative imaging time) ;
- Cost considerations.

DISCOVER has been designed to accommodate a set of advanced state-of-the-art "plug-and-play" problem-solvers based on artificial intelligence, mathematical programming and heuristic methods [11] [3].

The basic DISCOVER workflow structure from the bottom up is displayed in Figure 1. The structure involves sequential execution of high-level functions, namely, request/task preprocessing, collection plan generation, collection plan evaluation and collection plan selection respectively.

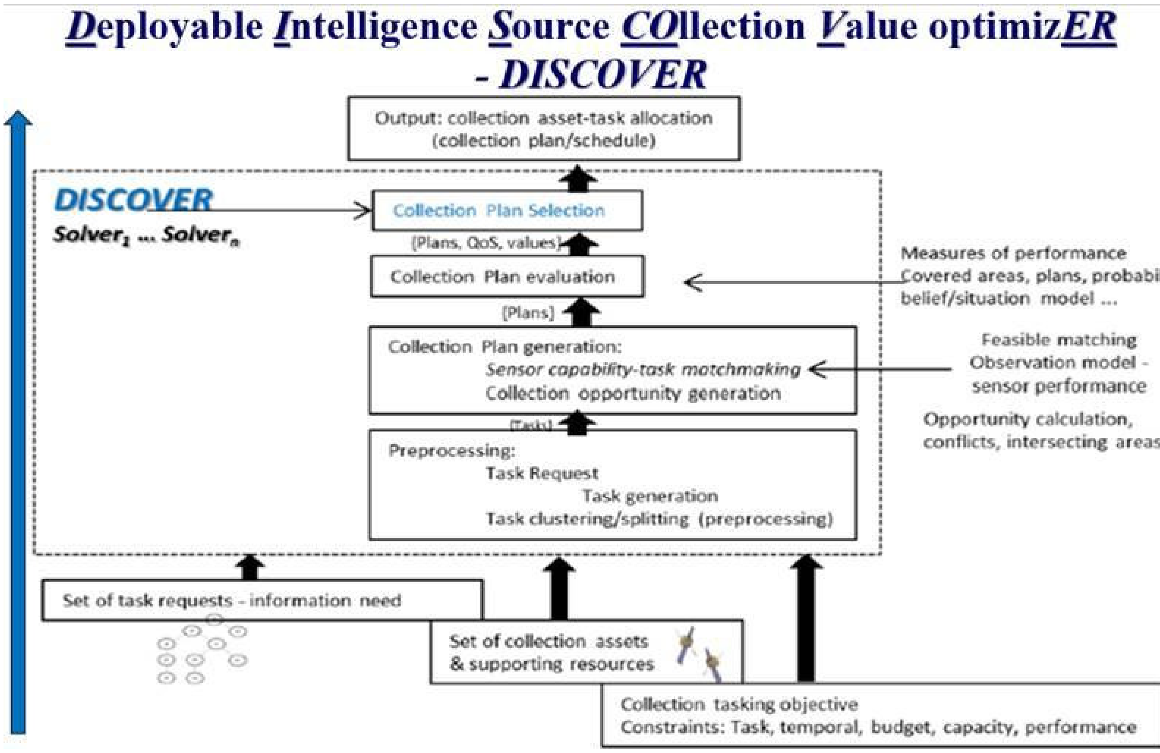

Figure 1: *DISCOVER workflow.*

A first DISCOVER prototype implementation relies on a service-oriented architecture (SOA) [25]. The proposed architecture prototype is based on a variety of data structure and services partly represented in Figure 2. The collection tasking problem specification (input/output) process reuses and extracts information (typically collection task, collection assets, collection tasking problem objectives and related constraints) through different CSIAPS/WISDOM/DISCOVER data access services. WISDOM is a federation of innovative, capabilities that can be composed and made interoperable in order to manage and exploit data, information and knowledge, and that can be organized or orchestrated to enable and support a specific business process assisting subject matter experts from situation analysis and decision making problem domains [25][24]. Other CSIAPS-based services are exploited to carry out task-asset matchmaking during collection plan generation and, collection plan evaluation. Accordingly, DISCOVER exploits the CSIAPS Guidance Expert System and relevant services to:

- Perform collection opportunity calculation;
- Extract collection opportunity content, intersecting areas opportunity couples, coverage plans, observation models or sensor performance (probability of success);
- Identify feasible “collection-asset-capability-to-collection-task” pairings (matchmaking);
- Extract imaging opportunity measures of performance (e.g., covered areas, probability of detection, ranking).

The Collection Plan Selection (CPS) service of the DISCOVER inventory incorporates a generic solver component to compute and generate a solution schedule. Solvers can be specialized (classes) to embed heuristics/exact methods using in-house or commercial problem-solving solutions.

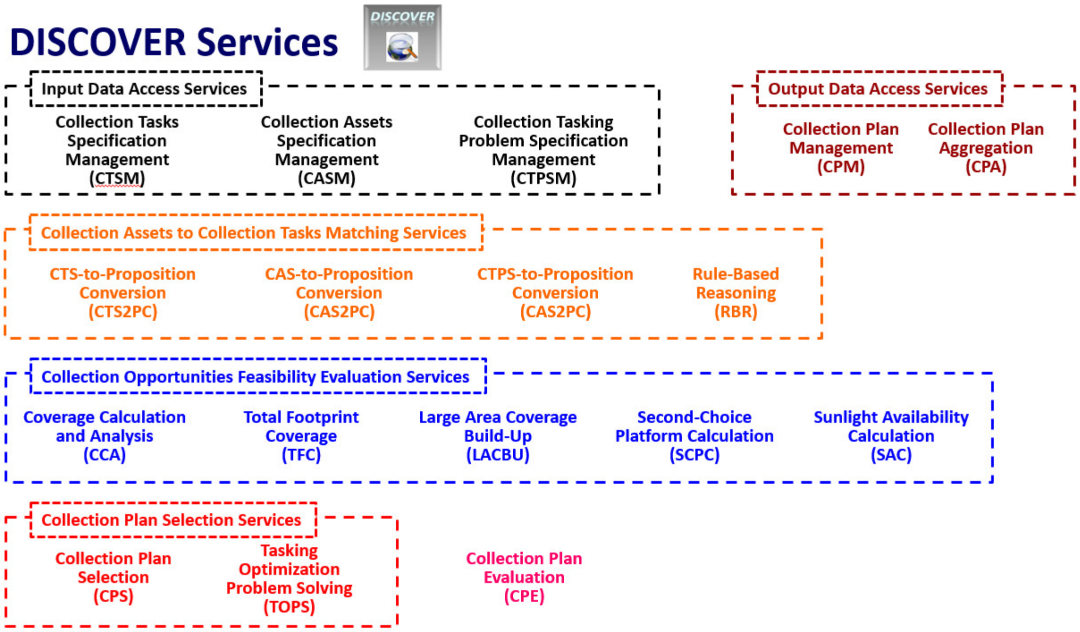

Figure 2: *Key DISCOVER services.*

Using these problem-solvers, DISCOVER returns a collection schedule solution (collection-asset-to-collection-task allocation) over a given time horizon.

A solution outcome to a user-defined image acquisition problem instance can be visualized under multiple representations (e.g., graphical, chart, textual). A graphical and chart views of a DISCOVER computed schedule solution recommended to a user for further analysis or selection are illustrated in Figure 3. Problem-solving optimization configuration can also be customized to user's needs and preferences.

The SOA-based DISCOVER 1.0 scheduling application is a proof-of-concept prototype to support near optimal automated tasking in order to bridge the gap between information needs and information-gathering. Focusing on open-loop multi-satellite collection tasking/schedule optimization, it consists in maximizing collection value subject to resource capacity and temporal constraints, cost, duty cycle; to improve service level, support comparative performance and sensitivity/robustness or "what-if" analysis, and enhance situational awareness while reducing run-time solution computation contributing to TCPED speedup. The prototype may be used as a tool to demonstrate use case optimal solution, cost-savings and additional request throughput, collection/information gains and provide some insight in sensor mix optimization.

DRDC has a strategic partnership to integrate CSIAPS, WISDOM and DISCOVER R&D prototype systems into a single unified platform referred to as the Holistic Ecosystem of Cutting-edge Services for Synergistic and Integrated Intelligence Production (HECSIP).

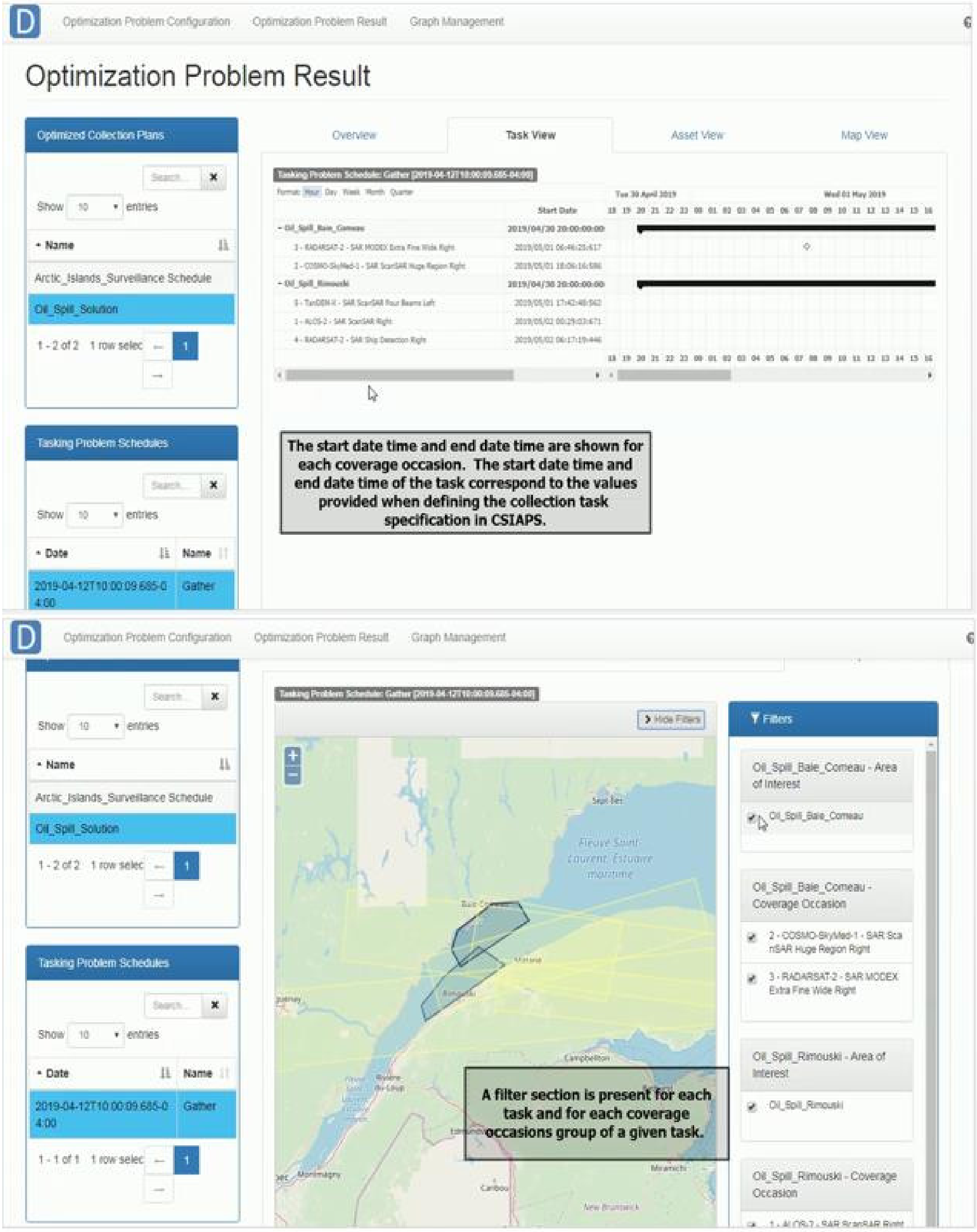

Figure 3: *DISCOVER selected solution outcome views (graphical/map, chart/task).*

5.2 Total::Perception

Developed in collaboration with the DRDC 05ed TCPED and 05da JICAC projects, the Total::Perception (T::P) solution [16–26] proposes an automated collection tasking capability emphasizing high-level information fusion (HLIF), prediction (through learning), Monte Carlo/"what-if" simulation and optimization. It aims at improving collection tasking performance using computational Intelligence techniques and HLIF methods to reduce the timeline of the TCPED cycle, cycle and in particular, the tasking and collection components, as well as assessing the feasibility of the approach in the context of a Maritime Domain Surveillance. The T::P's solution design captures the TCPED process, modelling the environment and ISR collection asset movements and behaviours involved in a surveillance mission. The capability allows the collection manager to automate platform positioning and sensor re-tasking optimization. It incorporates centralized and decentralized innovative planning solution approaches supporting multi-objective constrained optimization to automate near-optimal collection and downlink scheduling, assuming heterogeneous collection assets, including satellites. The proposed multi-objective optimization framework include elements such as collection value, service level or demand satisfaction and financial cost.

An overview of the proof-of-concept T::P services designed for perception management is pictured in Figure 4, briefly exposing key fusion, prediction, and simulation and optimization components. Accordingly, T::P may either query contextual knowledge to access relevant problem attributes, predict model-based situation evolution, optimize collection plan given feasible collection opportunities, and simulate collection plan execution using a simulation Engine for visualization or performance assessment purposes. T::P models target environment, collection assets and the TCPED process providing the collection manager with optimized plan recommendations.

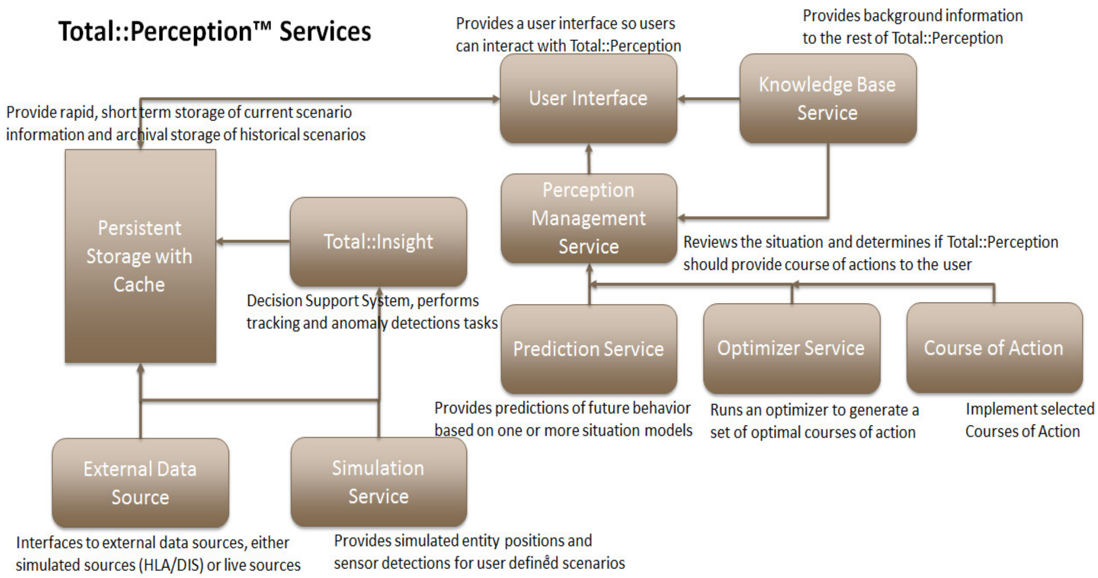

Figure 4: *High-level overview of Total::Perception from Abielmona et al. [16]. The diagram is a courtesy of Larus Technology and was reproduced with their permission.*

High-level information fusion—Building hierarchically information fusion (e.g., from object level up) the Total::Insight (T::I) component is used to estimate situational understanding defining multi-level situation evolution dimensions (e.g., kinematic, risk, threat, market, objective and environment-based).

Prediction—Prediction is achieved using machine learning. Accordingly, a predictor/classifier is trained using simulation to estimate possible evolution of a given situation. For instance, for a tracking task, target trajectory prediction based on situation evolution model dimensions instantiated from the T::I fusion component, primarily rests on a deep neural network to infer most likely evolution or behaviour. This process is then exploited to generate possible collection opportunities.

Simulation—The simulation engine is aimed to:

- Generate and run discrete-event scenario specifications;
- Model high-fidelity of heterogeneous assets (entities, space, air, surface and ground platforms in real or simulated time; sensor models: fixed radar, synthetic aperture radar [SAR], ground mobile radar, high-frequency surface wave radar [HFSWR], automatic identification system [AIS]). These sensors can be embedded on maritime, air, space or land platforms. Simulation captures deployment/execution behaviour (activity models, paths, field of view, detection);
- Generate feasible imaging collection opportunities for each collection asset-task combination;
- Evaluate a candidate collection task plan. Specific measures of performance parameters (e.g., coverage estimation, probability of detection or success, state variable estimation error, confidence level estimation over possible hypotheses, risk level) are estimated using plan execution simulation. Performance assessments are then used by the optimization engine to maximize collection value and recommend the best collection plan to meet task demand;
- Visualize and rehearse computed collection plan execution for validation purposes.

Decision-making—The optimization engine is responsible for heterogeneous collection asset tasking/scheduling (supporting platform mixes such as a virtual satellite constellation) coupled with a feasible downlink scheduling solution. It accounts for a single or multiple objectives such as collection value, task demand satisfaction (service level) and financial cost, looking for the best trade-off solution among all non-dominated solutions. The T::P optimization engine integrates the DRDC Genetic Algorithm-based collecTion scHedulER (GATHER) [11], as well as the best-known evolutionary multi-objective optimization algorithm (NSGA-II), and relying on solution dominance to solve the multi-asset collection tasking/scheduling problem. The advocated "anytime" algorithm is interruptible and can provide and/or recommend multiple solutions to the user at any time. The optimizer service illustrated in Figure 4 has been designed to host problem-solvers such as the ones introduced earlier in Section 3.1.2. The optimization engine supports decentralized collection tasking as well, managing a virtual agent/sensor network (e.g., virtual satellite constellation). It integrates decentralized collection tasking solution approaches introduced in Section 3.2.

In summary, the T::P TRL-6 prototype includes the following features/novel capabilities:

- Centralized and decentralized collection asset (including satellite constellation) observation and downlink scheduling;

- Exploitation and adaptation of best state-of-the-art computational intelligence single and multi-objective algorithms to convey collection gain, cost-savings and task service level improvement;
- Mixed HLIF, prediction and simulation capability enhancing situational awareness, leading to a tighter integration between information need and information-gathering;
- Automated near-optimal multi-objective (user-defined) collection scheduling that can accommodate a variety of heterogeneous collection assets;
- Design of virtual satellite constellation, applicable to combined and commercial collection assets;
- Near real-time execution;
- TCPED lead time reduction.

The T::P proof-of-concept prototype compresses the TCPED cycle automating and optimizing near real-time collection tasking, while providing the flexibility to dynamically specify user-defined collection tasking optimization objectives. It has been showcased for a combined Arctic surveillance air intrusion and dark ship scenario.

6 Summary and Potential Impact

New research and development intelligence collection concepts and automated decision support/planning capabilities to support/recommend/advise the collection manager on effective and efficient resource allocation have been presented. Focusing on the multi-satellite image acquisition scheduling problem use case, from a low-density, high-demand collection asset perspective, it aimed at addressing some of the intelligence collection gaps, deficiencies and challenges reported in “Intelligence Collection Investigation” [1]. Accordingly, new operations research and artificial intelligence contributions in novel static and dynamic settings for centralized and decentralized decision-making contexts were proposed. These include a new tool suite of open-loop, closed-loop, mixed (open-and-closed loops) problem-solvers as well as proof-of-concept decision support prototypes (recommenders) for effective collection tasking of real or virtual satellite constellations. The proposed approach simultaneously captures coverage, uncertainty (probability of success) and imaging quality (e.g., resolution, look angle), subject to additional collection asset and constraint diversity, and extended task abstraction. It introduces a weighted task decomposition structure coupling composite requests through spatial and temporal task dependencies, reflecting more realistic mission complexity. The developed technology solution concepts has shown automated and optimized collection tasking feasibility and proved to be fast, reducing collection manager’s cognitive load while providing situational awareness enhancement and improved service level.

The overall reported research contribution benefit the Canadian Armed Forces (CAF) in many respects. It first advises DRDC, CFITNCOM and CJOC on intelligence collection problems and challenges and, on command and control Joint ISR enterprise tasking tools to assist in optimizing the utilization of a complex set sensors and platforms. It informs CFINTCOM, DG SPACE, Royal Canadian Air Force (RCAF) and the Defence enhanced Surveillance from Space Program (DESS-P), on DG SPACE Space-based Surveillance future requirements [14] [27] [26]. It namely conveys some guidance on prospective collection planning performance requirements in terms of automated collection tasking optimization, impacting future RCM follow-on enhancements. Accordingly, as a technology enabler, feasible constrained optimization would help define or validate suitable scenario/mission-based performance requirements. It also provides DG SPACE with an insight on promising decision support capabilities to improve situational awareness on target tracking and identification, and of routine traffic in and through Canadian territory. The above findings also notify the CFINTCOM Defence Intelligence Enterprise Renewal initiative (CFINTCOM/DIER) on new collection management concepts, tools deployment. They suggest a new direction on building CFINTCOM’s advanced intelligence support capacity to support operations, namely, on innovative solutions to surveillance challenges in the North, offering a different collection tasking perspective while evolving toward suitable enterprise information integration. The reported contribution on combined simulation, fusion, prediction, and optimization further informs CJOC (e.g., the Joint ISR Management System (JIMS) initiative) and Special Operations Forces (SOF) through the Canadian Forces Joint Warfare Centre (CFJWC) on Joint ISR concepts, resource allocation option analysis, and ISR optimization tools deployment. It also advises DRDC 02CB Empowered Dispersed Operations in the Digital Age (EDODA) project under the Army portfolio on solution reutilization/dual use technology for optimized collection automation (Army command, control, communications, computers, intelligence, surveillance and reconnaissance (C4ISR) at the tactical edge).

From a DRDC standpoint, this research endeavour empowered the development of technical expertise and knowledge, fostered multiple collaborative efforts and, networked with University, other labs (DRDC – Ottawa Research Centre, Space and ISR Applications [SIA] Section), and international Defence initiatives (e.g., TTCP Intelligence, Surveillance, Target Acquisition and Reconnaissance [ISTAR]), leveraging on technology and capacity in command and control and intelligence. It positioned DRDC Valcartier Command, Control and Intelligence (V/C2I) Section to take on future challenges on intelligence collection and productively build on national and international collaboration. Some initiatives for technology transition is ongoing through utilization licenses granted to industry, namely, Thales and SATWII Inc. for the GATHER [11] and QUEST [3] problem solvers respectively.

7 Recommendations

Some recommendations are formulated along institutional endorsement, technology exploitation and future R&D work extensions. In order to benefit RCM follow-on, we first advise DG SPACE to include collection tasking optimization as a separate future space-based surveillance requirement and RCM follow-on, offering potentially significant information gains and service level improvement. Then, dual use technology and solution deployment for automated collection tasking is strongly advocated across the different environments. Accordingly, ISR simulation/optimization tool reutilization, exploitation and adaptation are expected to benefit CFINTCOM (e.g., Arctic intelligence and maritime domain awareness), as well as CJOC and SOF through the CFJWC. Army tactical C4ISR could also benefit from these technology enablers through the Decision-Action Cycle Optimization and Technology Adoption (DACOTA) strategy advocated by Directorate Land Requirements (DLR2), while informing Land ISR modernization capital project. Finally, we recommend to the Director General Joint Force Development (DG JFD) to conduct future research and development on intelligence collection concepts and automated decision support/planning to handle growing complexity. Hierarchical complexity refinements include: uncertainty management; task multiplicity and diversity; multi-intelligence deployable sources; heterogeneous asset mix optimization; tighter coupling between sense making and collection tasking; advanced distributed collection tasking; the combination of satellite imaging and downlink scheduling problems, further relying on mixed ground and space-based communication asset networks; and possibly some tighter WISDOM-DISCOVER-CSIAPS integration. This will pave the way toward the development of an advanced collection and asset manager assistant, supporting the collection manager in selected deployments, demonstrations and exercises.

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List of Symbols/Abbreviations/Acronyms/Initialisms

AIS	Automatic Identification System
CAF	Canadian Armed Forces
CF	Canadian Forces
CFINTCOM	Canadian Forces Intelligence Command
CFJWC	Canadian Forces Joint Warfare Centre
CJOC	Canadian Joint Operations Command
CM	Collection Management/gestion de la recherche
COIC	Commandement des opérations interarmées du Canada
CoM	Coordination Mediator
COMRENSFC	Commandement du renseignement des Forces canadiennes
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance
CSIAPS	Commercial Satellite Imagery Acquisition Planning System
DACOTA	Decision-Action Cycle Optimization and Technology Adoption
Deep CLUE	Deep Collection Learning in Uncertain Environment
DESS-P	Defence Enhanced Surveillance from Space Program
DG – Espace	Directeur général – Espace
DG JFD	Director General Joint Force Development
DG SPACE	Director General Space
DIER	Defence Intelligence Enterprise Renewal
DISCOVER	Deployable Intelligence Source Collection Value optimizer
Dis m-SatCSP	Distributed, Multi-Satellite Intelligence Collection Scheduling Problem
DLR2	Directorate Land Requirements
DRDC	Defence Research and Development Canada
DRL	Deep Reinforcement Learning
DynaQUEST	Dynamic Quadratically constrained Program Solver Technology
EDODA	Empowered Dispersed Operations in the Digital Age
EO	Electro-Optic
GATHER	Genetic Algorithm-Based Collection scheduler
GBR	Gestion des besoins en renseignement
HECSIP	Holistic Ecosystem of Cutting-Edge Services for Synergistic and Integrated Intelligence Production
HGA	Hybrid Genetic Algorithm
HFSWR	High-Frequency Surface Wave Radar

HLIF	High-Level Information Fusion
IMINT	Imagery Intelligence
IRM	Iintelligence Requirements Management
ISR	Intelligence, Surveillance and Reconnaissance
ISTAR	Intelligence, Surveillance, Target Acquisition and Reconnaissance
JFD	Joint Force Development
JICAC	Joint Intelligence Collection and Analysis Capability
JIMS	Joint ISR Management System
JISR	Joint Intelligence, Surveillance and Reconnaissance/renseignement, surveillance et reconnaissance interarmées
m-SatCSP	Multi-Satellite Collection Scheduling Problem
MCR	Mission de la Constellation RADARSAT
MIQP	Mixed-Integer Quadratic Program
MO-GATHER	Multi-Objective Genetic Algorithm-based collection scheduler
MOSAIC	Mixed/Multi Overlapping Sub-Area composition Coverage
MY_PICC	Myopic Planning-based Image acquisition heuristic
QUEST	Quadratically constrained program Solver Technology
R&D	Research and Development
RA	Resource Allocation
RCAF	Royal Canadian Air Force
RCM	RADARSAT Constellation Mission
SAR	Synthetic Aperture Radar
SOA	Service-Oriented Architecture
SOF	Special Operations Forces
SIA	Space and ISR Applications
T::P	Total::Perception
TCPED	Tasking, Collection, Process, Exploitation and Dissemination
TRL	Technology Readiness Level
V/C2I	Valcartier Command, Control and Intelligence
VRPTW	Vehicle Routing with Time Windows

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Under the Defence Research and Development Canada (DRDC) 05da Joint Intelligence Collection and Analysis Capability (JICAC) project, this Scientific Report proposes innovative contributions providing advanced intelligence collection tasking support to operations as part of the intelligence requirements management and collection management (IRM/CM) capability. It reports on the design of novel collection tasking optimization tools aimed at supporting the collection manager in dealing with complex tasks and collection assets. It summarizes new research and development intelligence collection concepts and automated decision support/planning capabilities to support/recommend/advise the collection manager on effective and efficient resource allocation. Focusing on the multi-satellite collection scheduling use case problem, new technology solution concepts leading to fast, automated and optimized collection tasking, providing service level improvement and enhanced timely situational awareness are briefly reported. Underlying concept novelties borrowed from artificial intelligence and operations research aim at maximizing collection value, subject to a variety of task, opportunity, resource capacity, temporal and cost constraints. The Report summarizes technical achievements describing new fast, automated and optimized collection tasking solution approaches and prototype recommenders to schedule real/virtual multi-satellite constellations. It copes with deficiencies and challenges such as myopic (single task-focused) and/or ad hoc intelligence collection tasking approaches, unsuitable centralized/decentralized open and closed-loop resource management methodology or framework to ensure static/dynamic planning or handle constraint multiplicity/diversity and uncertainty management. The Report also aims at informing Canadian Forces Intelligence Command (CFINTCOM), Director General Space (DG SPACE), Canadian Joint Operations Command (CJOC) and key military Joint Intelligence, Surveillance and Reconnaissance (JISR) stakeholders as well as the Research and Development (R&D) community on main technical findings and follow-on recommendations. It underlines the value of space-based resource management optimization to enhance situational awareness, target detection, tracking and identification through the Canadian territory, including the Arctic region.

Dans le contexte du projet RDDC 05da Joint Intelligence Collection and Analysis Capability (JICAC), le présent rapport scientifique propose des contributions innovantes offrant un soutien avancé en matière de cueillette du renseignement aux opérations dans le cadre de la capacité de gestion des besoins en renseignement et de gestion de la cueillette (GBR/CM). Il rend compte de la conception de nouveaux outils d’optimisation de tâches de cueillette visant à aider le gestionnaire de cueillette à composer avec des tâches complexes et des ressources de cueillette. Il résume de nouveaux concepts de cueillette de recherche et développement et des capacités d’aide à la décision/de planification automatisées afin de soutenir/recommander/conseiller le gestionnaire de cueillette sur l’allocation efficace et efficiente des ressources. Misant sur le problème du cas d’utilisation de la planification de la cueillette multi-satellite, de nouveaux concepts de solutions technologiques menant à des tâches de cueillette rapides, automatisées et optimisées, résultant en l’amélioration du niveau de service et une meilleure connaissance de la situation sont brièvement décrits. Les nouveaux concepts sont inspirés de l’intelligence artificielle et de la recherche opérationnelle et visent à maximiser la valeur de la cueillette, sujet à une diversité de contraintes temporelles et financières et à d’autres contraintes reliées aux tâches, aux possibilités et aux capacités en matière de ressources. Le présent rapport résume les réalisations techniques décrivant de nouvelles approches de solution de cueillette rapides, automatisées et optimisées et des prototypes aviseurs pour céduler de réelles/virtuelles constellations multi-satellites. Il aborde les déficiences et les défis tels que les approches de cueillette du renseignement myope (axées sur une seule tâche à la fois) et/ou ad hoc, et une méthodologie ou un cadre de gestion des ressources en boucle ouverte et fermée centralisée/décentralisée inadéquate pour la planification statique/dynamique ou pour régir la multiplicité et la diversité de contraintes et la gestion de l’incertitude. Le rapport vise également à informer le Commandement du renseignement des Forces canadiennes (COMRENSFC), le Directeur général – Espace (DG – Espace), le Commandement des opérations interarmées du Canada (COIC), les principaux intervenants militaires dans le domaine du renseignement, de la surveillance et de la reconnaissance interarmées (JISR) ainsi que la communauté du secteur de la recherche et du

développement sur les résultats les plus importants et à leur fournir des recommandations. Il souligne la valeur de l’optimisation de la gestion de ressources spatiales afin d`améliorer l`éveil situationnel, la détection, le traçage et l`identification de cibles sur le territoire canadien, y compris l’Arctique.