NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

2018 Workshop on Autonomy for Future NASA Science Missions: Earth Design Reference Mission Reports

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Introduction

Autonomy is changing our world; commercial enterprises and academic institutions are developing and deploying drones, robots, self-driving vehicles and other autonomous capabilities to great effect here on Earth. Autonomous technologies will also play a critical and enabling role in future NASA science missions, and the Agency requires a specific strategy to leverage these advances and infuse them into its missions. To address this need, NASA sponsored the 2018 Workshop on Autonomy for NASA Science Missions, held at Carnegie Mellon University, October 10-11, 2018.

The Workshop goals included:

- Identifying emerging autonomy technologies (10-15 years) that will:
  - Enable or enhance mission capabilities
  - Reduce risk
  - Reduce cost
- Identifying potential collaborations, partnerships, or linkages involving government, industry, and/or academia to enable these technologies

Capturing crosscutting autonomy technology requirements for future NASA missions
Over 90 individuals from industry, academia, and NASA participated in the workshop, which included presentations by keynote speakers, panel discussions, and small group discussions.

To provide structure for workshop discussions and post-workshop analysis, NASA established eight teams to examine the following Design Reference Mission (DRM) areas: Astrophysics, Earth Science, Heliophysics, Mars, Moon, Ocean Worlds, Small Bodies and Venus. Each DRM team was led by a scientist and a technologist, and team members consisted of workshop participants with relevant experience and interest. NASA asked each team to develop one or more mission scenarios that would be enabled by infusion of autonomous technology. The Agency provided guidance to support these team discussions; in particular, NASA urged the DRM teams to "think out of the box" and to consider bold missions that would be enabled by autonomous technology to provide valuable science results. Each DRM team developed mission scenarios that included defined science objectives, capability and technology needs, system requirements, and a concept of operations. Teams also identified gaps where autonomy technologies and other supporting technologies need to be developed and/or infused to enable each mission.

The DRM teams conducted small group discussions at the workshop and then presented a summary of their findings to all workshop attendees. Each DRM team continued to refine its mission scenarios after the workshop, creating both a full report and a summary report to document team findings. DRM teams also reported results at the December 2019 meeting of the American Geophysical Union.

This document contains the full report and summary report generated by the Earth DRM team. Full and summary reports generated by all eight DRM teams, plus a summary of workshop results are available online.

The Earth Design Reference Mission Report

Part I: Abstract

Few Earth-observing satellites in operation today have instruments that can be used to stare at a specific Earthside location. Almost all of these are manually commanded, using several days of instrument command formulation and testing, followed by transmission to the platform mission operations center, followed by more testing and eventual upload to the satellite with further testing and confirmation.

Recently, the Earth Science community has experimented with ballistic constellations of satellites—small spacecraft and their associated instruments—with autonomous control of instruments and aircraft flights. This has revealed new opportunities for studying physical phenomena and natural processes that previously were not accessible from space. It also allows a more direct coupling with models, including the possibility of directing observations to update models, based on assessment of the quality of model output. The Earth Design Reference Mission (DRM) team proposes the following DRM scenario in which autonomy can be incorporated to enable and enhance innovative Earth-observing systems.

Model-Driven Observing Strategy.

This is an observing strategy for Earth science driven by models. As the model needs more data, it provides direction to the observing system to collect specific data from certain regions and of specific conditions (i.e., sea-surface temperature in the Sea of Japan) and report it back by the fastest possible route. The resulting model forecasts are then evaluated to verify the needed improvements.
Autonomy would be enabling for this DRM for workflow management, model quality assessment, satellite control, and tasking prioritization and deconfliction, among other capabilities.

Critical Autonomous Technologies

The critical autonomous technologies that will enable this scenario are **situation and self-awareness, reasoning and acting, collaboration and interaction**, and **engineering and integrity**, including:

- *Sensing and perception*
- *State estimation and monitoring*
- *Event and trend identification*
- *Anomaly detection*
- *Behavior and intent prediction*

- *Verification and validation*

These technologies will enable the following capabilities:

- Selection of the appropriate asset
- Resolving conflicts and issuing the necessary tasking without human intervention
- Monitoring workflow, detecting and compensating for faults
- Verifying completion of the improved forecast

Supporting technologies that are needed for this scenario include:

- Onboard processing
- Adaptive computer security (multi-mission, threat response)
- Models capable of continuous operations and identifying regional degradations
- Assimilation models supporting irregular input
- Collision avoidance as collaboration with other assets (i.e., non-NASA)
- Autonomous mission evaluation; including testing, safety evaluation, threat detection.

Findings

The Earth DRM team finds that the following actions and activities would facilitate implementation of the DRM scenario described above. The next step would be to establish and debug a ground-based testbed upon which to develop and evaluate the integration capabilities needed to make this functionality available to the Earth-science community. This experimental environment would be used to evaluate the current state of the various components. It would also be used to evaluate alternative observing strategies and to assess the relative complexity of each. Other next steps include:

- Developing computational forecast models of physical processes and natural phenomena that run in a more real-time and continuous way.
- Further developing the airborne mission-management software to be used with models, in situ and on-orbit components, as well as airborne assets.
- Developing a mission-operations concept in which the role of humans is to oversee and potentially override the autonomous system. This involves a significant human-factors analysis and evaluation, possibly similar to what is being done in NASA's Aeronautics Research Mission Directorate (ARMD) or the Human Exploration and Operations Mission Directorate (HEOMD).
- Developing a fairly comprehensive autonomous Model-based Safety Analysis capability so that all autonomous and manual decisions are evaluated as they are being formulated for safety (and collision avoidance) implications.

Part II: The Case for Earth

Recently, the emergence of small spacecraft as science-quality observing platforms has created a new set of opportunities, as noted by the National Academy of Sciences in the 2017 Decadal Survey. First, some of the traditional observing strategies can be performed with less expensive platforms so more instruments can be placed in orbit to perform global-mapping missions with higher revisit rates, when appropriate. Second, the use of constellations of satellites permits study of transient or transitional natural phenomena or natural processes that could not have been observed from space before. Third, multiple spacecraft can be used to improve measurement quality and signal-to-noise ratios when used as an array, flying in formation all aimed at the same location.

Flying strings of satellites permits longer duration observations of the same location than afforded by single satellites with long-revisit rates. Flying an array of satellites permits the observing of a phenomenon simultaneously from different angles, either with the same or different instruments. Flying a configuration of satellites with the same instruments can also be used to form a phased array which can improve spatial resolution, or accuracy. Today, such constellations fly in a pattern because they are injected into certain orbits on ballistic trajectories with limited manual orbit adjustments. Few satellites today have instruments that can be used to stare at a specific Earthside location; almost all of these are manually commanded, using several days of instrument command formulation and testing, followed by transmission to the platform mission operations center, followed by more testing and eventual upload to the satellite with further testing and confirmation. Both types of these largely manual adjustments have considerable latency built in.

The emergence of small spacecraft has also generated a rapidly growing commercial remote sensing industry due to the reduced cost of acquiring, launching and maintaining an operational observing system. This means that instrument output is available for a price from devices not owned by the Federal Government. Furthermore, this commercial market has also created a new industry in commercial ground station services, such as those by Swedish Space Corporation, Konigsburg Space and Amazon Web Services, thereby reducing the latency in downlinking observational data due to ground station location and availability.

These new observing strategies are useful in a variety of missions to support both research and operational capabilities. New research can be accomplished leading to a more-complete understanding of transient and transitional natural phenomena and physical processes where the time constants involved required multiple observations in close proximity and others where the necessary revisit rate is on the order of hours. Table 1 describes the science domain and new studies that are enabled this way.

Domain	Physical Processes	Revisit Rates
Biodiversity	● Green wave ● Diurnal vegetation activity ● Carbon transfer	Ideally, hourly. At least every 3 hours during daylight
Cryosphere	● Sea ice formation/melt ● Ice flows ● Changes in water flow under glaciers ● Seasonal changes in soil	Daily
Water Cycle	● Surface water ● Snow accumulation/melt ● Soil moisture ● Flooding (modeling and disaster response)	Daily
Air Quality	● Planetary boundary layer changes	2-3 times daily or less

Table 1: Sample of Earth Science Domains and Observations Enabled by the New Observing Strategy (Note: Revisit rates require validation)

The Earth-science community has experimented with ballistic constellations of satellites, with small spacecraft and their associated instruments, and with autonomous control of instruments and aircraft flights. This work has revealed some opportunities for studying natural phenomena and physical processes that previously were not accessible from space. These mission scenarios also allow a more-direct coupling with models, including the possibility of directing observations to update models, based on assessment of the quality of model output.

This concept supports both research and operational models. In the case of research, the investigator seeks to improve the representation of the scientific knowledge of the relevant phenomenon; by manipulating an appropriately designed model, it could be used to drive the observing regime needed to collect relevant data to study specific phenomena. In the case of operational forecasting, the operator seeks to improve the skill level of the model by setting a minimum threshold at which the system would recognize the need for improving skill level, task the observing system to acquire the observations needed, recompute the forecast, and validate the improvements as the ones needed.

Another onboard function could be to prioritize data to be transmitted, e.g., when an anomaly is detected.

Part III: Design Reference Mission

DRM Scenario: A Model-Driven Observing Strategy

This DRM describes an observing strategy for Earth science driven by models. As the model needs more data, it provides direction to the observing system to collect specific data from certain regions and of specific conditions (i.e., sea-surface temperature in the Sea of Japan) and report it back by the fastest possible route. The resulting model forecasts are then evaluated to verify the needed improvements.

This approach is useful in both research and operations, depending on what the model is trying to do. In the case of research, it might be to improve deficiencies in the understanding of physical processes, as reflected in the model. In the case of operations, it might be to maintain a minimum level of quality in the forecast skill level.

The Concept of Operations

Currently, models of natural processes are run in a batch strategy, either on demand or on a recurring schedule. Observational data is assimilated in batches and then fed into the initialization of the model run. Future models are envisioned to run on a continuous basis, feeding in new data as it becomes available. Such models are expected to be used in areas such as weather, surface hydrology, snow, precipitation, oceanography, atmospheric composition and surface biology and geology.

For operational forecasting, as the model runs and identifies diminishing forecast-quality in a location/region, it identifies observational data that is needed to restore quality. An autonomous supervisory system then determines the most effective strategy for collecting the needed data, tasks the observation elements (satellite, airborne, ground or in situ) to collect and report data. The data are then assimilated and the model components updated, and the quality re-assessed to ensure the expected improvements have occurred.

For research into a process or phenomenon, this approach would run a repeating test/debug cycle on models to improve their ability to predict the behavior of the physical processes and natural phenomena. A researcher would assess the efficacy of the model and then define an experiment or a campaign to collect data, do analysis, adjust the model and repeat the process, making incremental improvements to more accurately understand and represent specific parts of a process or phenomenon.

Control of the observing assets will be handled through a supervisory program that runs collects and analyzes data about both the environment and the observing system. The autonomous operations are supervised by human operators that adjust high-level priorities and monitor an internal diagnostic system that executes contingencies and directs maintenance and repair actions when needed. Computer security threats are similarly detected and mitigated by the supervisory system, alerting operators to emerging abnormal operations and keeping them apprised of the issues as they emerge.

Assumptions

- Models have dependable mechanisms for assessing quality of forecasts (e.g., skill level) and can identify observations at the sub-global scale needed to improve quality;
- Models of physical processes and natural phenomena of interest are developed in such a way to leverage updated non-global observational data at the regional level rather than requiring new global input to have any impact.

Autonomy is needed for this DRM for the following purposes:

- Workflow management, including assessing the quality, determining the optimum resource to use to collect the needed data at the time it is needed.
- Model quality assessment throughout the model run.
- Control of the satellites, mission adjudication and prioritization, and deconfliction of tasking.
- Maintain system operations for an indefinite period of time, including system calibration, executing contingency plans, and maintenance and repair actions.
- An effective presentation of just the right amount of information to keep the human aware of the state of the system under varying conditions. Some characteristics that might require operator intervention include the quality of the forecast, resource consumption, etc. This will require an entirely new approach to console presentation to ensure humans play an appropriate role.

The Autonomy Capabilities needed:

Selection of the appropriate asset. When a model indicates it needs data, there may be several choices of instruments and platforms to provide that data; they may be constrained by the quality and availability of the set of instruments. Autonomy would be needed to select and task the measurement capability. The accuracy and the characteristics of the measurement ability of each instrument (or class of instruments) affects its ability to satisfy the needs of the model to bootstrap itself into a higher-quality forecast. Adequate observations may come from multiple instruments on different platforms from different vantage points. This complex optimization requires autonomy to be accomplished in time and to create and check the observing instrument/platform tasking.

Resolving conflicts and issuing the necessary tasking without human intervention. Time scales for tasking are at the second and minute level and are likely to be substantially different each time they are needed. Human operators are unable to respond as quickly and with low enough error to manually perform the optimization and subsequent tasking.

Monitoring workflow, detecting and compensating for faults. For an autonomous, model-driven observing system to operate it must monitor the health of the system—at both the component level and the system level—so that it can task functional components. In a complex interconnected system, with many different demands and many pathways and thousands of failure modes, continuous monitoring and decision making will be necessary to identify faults and to reroute around them. Keeping humans informed and aware without delaying fault repair will be critical. Human operators will become quality assurance and adjusters of the system, which means they need a console and controls that enable high-level supervision, not micromanagement.

Verifying completion of the improved forecast. Forecasts are complex representations of a non-linear, inhomogeneous, dynamic natural system. Improvements to either research or operational models expected as the result of observing system tasking must be validated to ensure the resulting forecast actually supplied the improvements expected and, if not, additional observations and or processing may be required. The autonomous observing system must assess these improvements, alert the operators and direct additional corrective action. Analysis of the resulting quality, after the forecast has been started and at various stages, will be necessary—as well as an appropriate level of information about success to be presented to the human supervisor.

The Autonomous technologies needed for all of these capabilities:

- Algorithms for use in autonomy
- Retasking
- Optimization of multiple heterogeneous assets
- Dynamic recalibration on-orbit
- Intelligent data understanding
- Low-load algorithms for detecting desired observations
- Model self-assessment and identification of corrective action

Achieving these autonomous technology capabilities will require advancements in all of the elements listed in the Autonomous Systems Taxonomy (AST) document developed by NASA's Autonomous Systems Capability Leadership Team.

Other non-autonomous technologies needed to support these capabilities:

- Onboard processing

- Adaptive computer security (multi-mission, threat response)
- Models capable of continuous operations and identifying regional degradations
- Assimilation models supporting irregular input
- Collision avoidance as collaboration with other assets (i.e., non-NASA)
- Autonomous mission evaluation; including testing, safety evaluation, threat detection
- Human-machine interface when the human oversees a system instead of operating it

The Relevant Research and Development Projects for this DRM

- Advanced Information Systems Technology (AIST) Competed Projects (2005-2022)
- Intercalibration Theory Study (NASA Earth and Space Science Fellowship) (2019)
- AIST Blockchain Study (2018)
- Trade-space Analysis Tool for Constellations (TAT-C) (GSFC) (ongoing)
- Multi-platform mission planning and operations (Ohio State University) (ongoing)
- Amazon Web Services (AWS) Groundstation as a Service Experiment (JPL) (2019)
- Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA) processing and opportunistic data communications experiments (JPL) (2019-2020)
- AIST New Observing Strategy (NOS) ground test bed (2019-2020)
- Defense Advanced Research Projects Agency (DARPA) Blackjack (ongoing)
- United States Geological Survey (USGS) Innovation Center Software Defined Radar (SDR) (ongoing) for soil moisture
- Starling/Shiver Project (NASA Ames Research Center, U.S. Air Force)

The Potential Challenges, Risks, or Questions for this DRM

Most of the technologies needed for this type of observing strategy have been developed and demonstrated for other purposes. However, the integration has not. The new autonomy is primarily needed to integrate the components into a working, cohesive, large-scale system. This model-based observing strategy represents a major shift in the design of certain missions, including those that observe transient and transitional phenomenon and events. This effort would require a progressive demonstration of the capabilities and eventually a demonstration of the science value of the observing strategies that are dependent upon the autonomy. Full implementation would be degradable to a manually operated mission with substantial reduction in science data, but building this degradation into the mission is not a common practice in NASA. This is a radically more-complex observing system than we use today, but offers substantial improvements to the types of phenomena/processes we can study. The sociology of the science community represents a substantial risk, in its skepticism of new technologies and the ability to conceptualize what the potential is, what risks need to be retired, and how to experiment with the technology to retire risks. Demonstrations of these capabilities are needed to show the value to the science community.

To be truly effective, this type of observing strategy requires collaboration among a wide range of separate and independent entities. Most of the components have been or will be developed by different organizations and establishing the collaboration will be another difficult problem. Current models of natural phenomena and physical processes are batch-oriented, computationally intensive, and slow. Both production forecast models and research models assume the availability of batch-loaded assimilation data for initialization. Estimates of skill level are at a gross level and need to be regionalized to determine where, when, and how degradation of forecasts is occurring.

Autonomous flight-control software has been developed at the Defense Advanced Research Projects Agency and other Department of Defense facilities. This software does not interact with widespread distributed assets of wide variation and needs to be further developed to expand into in situ and on-orbit platforms, as well as airborne assets. It also needs to be integrated with human operators in an appropriate oversight/override role.

Part IV: Findings

For the Earth Science Program, selecting an appropriate set of research and applied science domains upon which to try experiments is necessary. To date, teams studying the Energy and Water Cycle (specifically, hydrology), Air Quality, and the Cryosphere have indicated needs for model-driven observing capabilities. Since much of the autonomy is in the integration of emerging, but relatively mature, components, the use of a ground-based testbed would be a useful way to demonstrate the value of a model-driven observing system and to debug the integration of the individual components. When a working and conceptually useful system can be demonstrated, the next step would be to fly one of the sensing nodes on orbit and demonstrate that the system as a whole would be useful and feasible. Then a full observing system could be developed with appropriate flight-mission components. The Earth DRM team finds that the following actions and activities would facilitate implementation of the DRM scenario described above.

- Develop a ground-based, multi-site, multi-party testbed to mature the technology integration and to enable development of technologies that can be integrated.
- Run experiments for each of the science communities needing persuasion of the value of this type of observing strategy and the ability of the autonomous operations to provide more and better data than the conventional approach.
- Develop a theoretical basis for intercalibration among instruments to enable integrated and near real-time data consumption as input into the control system.
- Develop computational forecast models of physical processes and natural phenomena that run in a more real-time and continuous way.
- Further develop the airborne mission-management software to be used with models, in situ, and on-orbit components, as well as airborne assets.

- Develop a mission operations concept in which the role of humans is to oversee and potentially override the autonomous system. This involves a heavy human-factors analysis and evaluation, possibly similar to what is being done in NASA's Aeronautics Research Mission Directorate (ARMD) or the Human Exploration and Operations Mission Directorate (HEOMD).
- Develop a fairly comprehensive autonomous model-based safety analysis capability so that all autonomous and manual decisions are evaluated as they are being formulated for safety (and collision) implications.
- Develop an effective model-based computer security capability for protecting assets from rapidly evolving cybersecurity threats and for monitoring and assessing the state of NASA-owned assets as well as those of other collaborators.

Part V: Earth DRM Team

The Earth Design Reference Mission team is comprised of:
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Earth Design Reference Mission Report Summary

Few Earth-observing satellites in operation today include instruments that can be used to observe a specific Earth location. Almost all of these missions are manually commanded, which requires several days of instrument command formulation and testing, followed by transmission of information to the platform mission operations center, followed by more testing and eventual upload of information to the satellite for further testing and confirmation.

Recently, the Earth Science community has experimented with operations of instruments located on different platforms at different vantage points in consort with one another. These experiments involve constellations of small satellites, aircraft, and in situ platforms. A key element of this capability is the autonomous control of instruments and aircraft trajectories.

Each platform's vantage point has its own strengths and weaknesses, but these assets can be combined to execute new observing strategies. This work has revealed new opportunities for studying natural phenomena and physical processes that were not previously accessible from space. New research can be conducted that will increase our understanding of transient and transitional phenomena and of physical processes where the time constants involved require multiple observations in close proximity or where the necessary revisit rate is on the order of minutes to hours. These new observational capabilities also allow a more direct coupling with models, including the possibility of directing observations to update models, based on assessments of the quality of model output.

The Earth DRM team suggests the following DRM scenario to take advantage of this new paradigm.

DRM Scenario: A Model-driven Observing Strategy

This scenario describes an observing strategy for Earth science driven by models. This DRM scenario involves obtaining data from mission assets (including a constellation of small satellites and possibly airborne, ground-based, or in situ elements), learning from the data, and then making real-time decisions to command the assets to collect additional data to verify and further refine models to improve the quality of predictions. This model-based scenario would be useful for both operational forecasting and scientific research.

For operational forecasting, as the model runs, analysis identifies diminishing forecast quality in a location/region and determines the observational data that is needed to restore quality. An autonomous supervisory system then determines the most effective strategy (and contingencies) for collecting the needed data, and tasks the appropriate observation elements to collect and provide data. When the data are returned and assimilated, the model is updated and the model quality is reassessed to ensure the expected improvements have occurred.

To conduct scientific research into a process or phenomenon, this model-based approach involves running a repeating test/debug cycle on models to improve their ability to predict the behavior of physical processes and natural phenomena. The researchers identify a class of phenomena to be studied (e.g., F2 tornadoes) and start running the research model. The model then tasks the observing system to identify and make observations of the instances of that phenomenon as they occur. A researcher assesses the efficacy of the model and then defines an experiment or a campaign to collect more data, do analysis, adjust the model, and repeat the process.

This DRM scenario requires a level of autonomy that is not currently available. Advancements in autonomy technology are required for this mission scenario to perform the following:

Select the Appropriate Asset: When the system indicates a model needs data, there may be several instruments and platforms available to provide that data and there may be constraints due to data quality or availability of the instruments. Autonomy would enable the system to select from multiple heterogeneous assets and task the optimal set of measurement capabilities.

Resolve Conflicts and Issue the Necessary Tasking without Human Intervention: Time scales for tasking are at the second- and minute-level and are likely to be substantially different each time they are needed. Human operators are unable to respond quickly enough and with low enough error to manually perform the optimization and subsequent tasking. There may be conflicting tasking from multiple sources (i.e., research and operational forecasting systems using the same observing assets) that would need to be prioritized based on goal-oriented mission re-planning strategies**.** Autonomy would allow the system to continuously re-task elements to accomplish mission goals without human intervention.

Monitor Workflow, Detect and Compensate for Faults: For an autonomous, model-driven observing system to operate reliably, it must monitor the health not only of the overall system, but also of the functional components, to effectively plan and assign tasks. In a complex interconnected system with many different demands, many pathways, and thousands of failure modes, continuous monitoring and autonomous decision making will be necessary to identify and mitigate faults. Autonomy would enable detection of faults and the execution of complex contingency plans to optimize system availability. Furthermore, autonomy would enable the system to monitor instrument performance and dynamically re-calibrate when necessary.

Verifying the Improved Forecast: Forecasts are complex representations of a non-linear, inhomogeneous, dynamic, natural system. Improvements to either research or operational models expected to result from observing system tasking must be validated to ensure the resulting forecast actually supplied the improvements expected. If expectations are not met, additional observations and/or processing may be required, and the changes incorporated into future mission operations. The autonomous observing system must assess these potential improvements to the model, alert the operators, and identify and direct additional corrective action. The system must also improve its own performance when shortcomings are identified. Autonomy would enable quick reaction and re-tasking if the results are not as expected for a complex set of observational assets.

To enable autonomy in this DRM scenario, advancements in the following supporting technology areas are required:

- Onboard processing
- Adaptive computer security (multi-mission, threat response)
- Models capable of continuous operations and identifying regional degradations
- Assimilation models supporting irregular input
- Collision avoidance and collaboration with other assets (i.e., non-NASA)
- Autonomous mission evaluation, including testing, safety evaluation, threat detection

- Algorithms to support autonomous operations, including low-load algorithms (e.g., use of look-up tables instead of calculations) to detect desired observations
- System assessment using multiple and distributed logs from various sources with varying authority

For NASA's Earth Science Program, selecting an appropriate set of research and applied science domains in which to initiate such experiments is necessary. To date, research areas including Energy and Water Cycle (specifically, hydrology), Air Quality, and Cryosphere have indicated needs for model-driven observing capabilities. Since much of the autonomy required to support this model-based observing strategy requires the integration of emerging—but relatively mature—components, the use of a ground-based testbed would be a useful way to demonstrate the value of a model-driven observing system and to debug the integration of the individual components. When a working and conceptually useful system can be demonstrated on the ground, the next step would be to fly one of the sensing nodes on-orbit and demonstrate that the system as a whole would be useful and feasible. Then a full observing system could be developed with appropriate flight-mission components.

Findings

The Earth DRM team finds that the following actions and activities would facilitate implementation of the DRM scenario described above:

1. Develop a ground-based, multi-site, multi-party testbed to mature the technology integration and to enable development of integrable technologies.
2. Run experiments for each of the science communities that need a demonstration of the value of this type of observing strategy to show how autonomous operations can provide more and better data than the conventional approach.
3. Develop a theoretical basis for intercalibration among instruments to enable integrated and near real-time data consumption as input into the control system.
4. Develop computational forecast models of physical processes and natural phenomena that run continuously and in real time.
5. Further develop the airborne mission-management software to be used with models and in situ and on-orbit components, as well as airborne assets.
6. Develop a mission-operations concept in which the role of the humans is to oversee and potentially override the autonomous system. This implementation will involve a heavy human-factors analysis and evaluation, possibly similar to what is being done in NASA's Aeronautics Research Mission Directorate (ARMD) or the Human Exploration and Operations Mission Directorate (HEOMD).
7. Develop a fairly comprehensive autonomous model-based safety analysis capability so that all autonomous and manual decisions are evaluated as they are being formulated for safety (and collision) implications.

8. Develop an effective model-based computer security capability for protecting assets from rapidly evolving cybersecurity threats and for monitoring and assessing the state of NASA owned assets as well as those of other collaborators.