NASA’s Responses to the GDC IRB Recommendations

1) **The GDC budget (total and yearly profile) needs to be corrected to be better aligned with plans, correct deficiencies identified, and to assign the proper UFE at the Project and NASA/SMD level.**

   Response: NASA concurs with the recognition that the project budget does not align with the current development plan, and is taking steps to resolve that discrepency.

2) **A system level optimization approach should be undertaken by the Project in the very near future to steer the plans for formulation and implementation towards global system level optimization and solutions, including designating a lead position whose job is to focus on the issues of supply chain, logistics, and production.**
   - A probabilistic risk assessment to inform trades for implementation of the Class C risk classification (e.g., Level 2 versus Level 3 parts, selective redundancy, etc.).
   - Define the trade space for instrument requirements against the spacecraft provider offerings so that there is clear understanding from the beginning.

   Response: NASA concurs with the recommendation to emphasize system optimization, and appreciates the suggested considerations. NASA has taken the recommended lead position under advisement. The GDC project is currently investigating the potential scope of work and necessary expertise to fill this role. Beyond that specific position, NASA has been focusing on procurement lead times and anticipated supply chain delivery delays, and will continue in that manner.

3) **The Project should aggressively address risks associated with non-recurring engineering, multiple unit production, supply chain, interfaces and instrument accommodation to reduce risk during the non-recurring phase,** such as:
   - Develop a fully integrated engineering unit (S/C and instruments) of sufficient fidelity to be upgradable to protoflight as 6th S/C for flight,
   - Downselect a suitable spacecraft/SI&T provider from two candidate in a two-step process, and
   - Explore other approaches designed to reduce the burden of the effort.

   Response: NASA concurs with the recommendation to aggressively address risks that the Project faces in development and the production of multiple copies of instruments and spacecraft. NASA will take the IRBs specific recommendations under consideration as we continue to evaluate options for reducing these risks.

4) **Life Cycle phases should be revisited to allow for the early development of the engineering unit S/C provider 2-step selection process.**

   Response: NASA partially concurs with this recommendation. It has been and remains NASA's intent to revisit the mission phase schedule once all elements of the project (e.g. spacecraft provider, all instrument providers) are incorporated in order to appropriately balance and optimize the development schedule. However, a two-step selection process for the spacecraft provider would carry procurement, technical, and schedule risks.

5) **Consistent with the guidance and intent of the 2013 Heliophysics Decadal survey and the mid-term assessment, NASA SMD, HPD, and the GDC Project should proactively advocate for**

GDC and its critical contributions to the Heliophysics System Observatory (HSO) within the science and stakeholder communities.

Response: NASA concurs with the recommendation for stakeholder engagement. This engagement spans responsibilities held at the GDC Project, HPD, and SMD levels. As part of an overarching communications strategy, stakeholder engagement at those three levels will be clearly incorporated.

6) **The leadership of the Project Scientist team should be empowered to speak authoritatively about GDC and assume prime responsibility for interactions with the community and science performance trades that enable cost effective system level solutions; RAA of the Project Scientist versus that of the Program Scientist need to be clear and unambiguous.**

Response: NASA concurs with this recommendation. HQ assigned the Project Scientist that prime responsibility following the completion of the GDC Interdisciplinary Scientist and Investigation procurement activities. NASA will document the roles and responsibilities in the GDC team guidelines.

7) **NASA should develop a strategy in close collaboration with NSF and other national and international GB facility operators for GB measurements (e.g., ISRs and FPIs) to calibrate and validate GDC measurements.**

Response: NASA concurs with this recommendation. NASA has had initial conversations with potential inter-agency and international partners and will continue to pursue those options. Information on collaborations will be released for the community's awareness as they are finalized.

8) **NASA should undertake a valuation exercise to assess the capability of the suite of simultaneous GDC, DYNAMIC-like, and GB observations, and to calculate the extent to which the collective contributions exceed the sum of individual element contributions.**
   - The exercise should include the development of complementary aspirational budgets to quantify the cost of maximizing the return on the collection of GDC, DYNAMIC like, and GB investments.

Response: NASA concurs with this recommendation for Division activities beyond the GDC project. NASA sees GDC as a strategic focus that can be used to significantly advance scientific understanding of the upper atmosphere and its coupling to the Sun, Earth's space environment, and the lower atmosphere. NASA pleased to see the IRB's endorsement of that vision. Further, NASA considers the identified observations to be part of a larger strategy that encompasses other spaceflight science investigations (Recommendation 11) and addresses long-term scientific needs (Recommendation 12). This strategy would be accomplished through synergy with other NASA missions, domestic and international partnerships, and coordination with ground-based observatories. These aspects have been a part of previous and on-going discussions, and NASA intends to continue in that manner.

9) **NASA should capture lessons learned and revisit the approach for interactions and engagement with the heliophysics community for missions in the early stages, particularly strategic missions.**
   - The approach for GDC was unnecessarily constrained, and eroded confidence in the plans and motivations.
   - Mission plans, definition, and early formulation processes should be open and transparent with the community to every extent possible.
   - Best practices for the conduct of an STDT (or equivalent) process should be captured and

normalized across NASA/SMD in the form of a handbook.

Response: NASA concurs with the recommendation on capturing lessons learned, and appreciates the IRB's inclusion of community perspectives to be addressed.

10) **Much stronger collaboration between NASA and other agencies, including NOAA NESDIS/OPPA, NOAA NWS/SWPC, Space Force, Air Force, and the Navy, as well as commercial stakeholders is urged to understand and proactively address space weather impacts on space assets and to develop plans to incorporate GDC data streams into operational models; coordination with NOAA NWS/SWPC which holds the federal mandate for space weather operations, is particularly encouraged.**

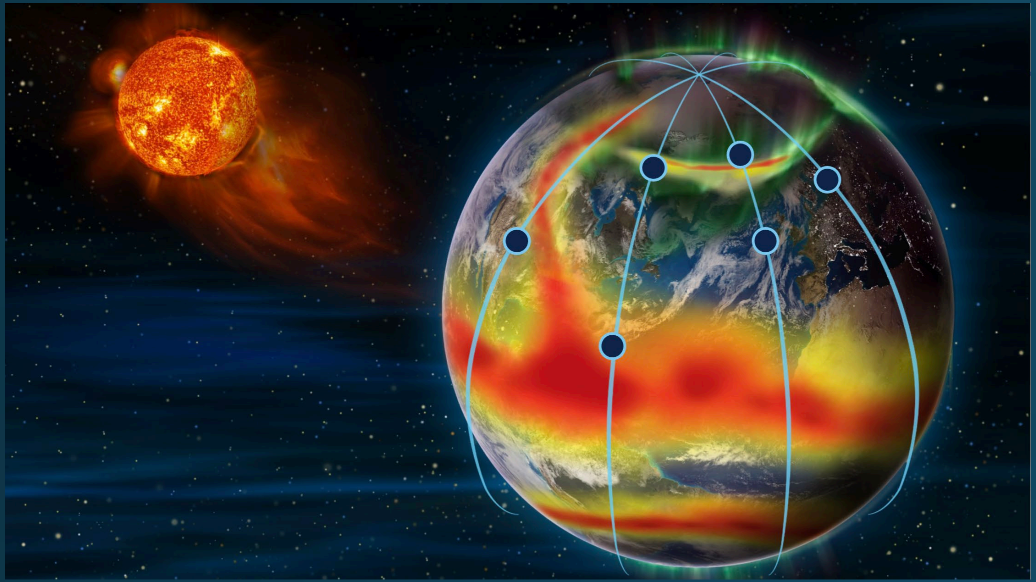
Response: NASA concurs with this recommendation, and has appointed a Deputy Project Scientist that has leading project involvement in these collaborations as one of their primary duties. These types of collaborations have been a part of previous and on-going discussions with inter-agency partners and NASA intends to continue in that manner.

11) **Given the international interest in the science that GDC will address, NASA should investigate plausible future collaboration with international partners, such as ESA, to augment and extend GDC science.**
    - Collaborations could include, instruments, hosted payloads, additional spacecraft and GB support.

Response: NASA concurs with this recommendation as part of a larger Division strategy, as discussed in the response to Recommendation 8. This aspect has been a part of previous and on-going discussions, and NASA intends to continue in that manner.

12) **NASA should investigate the additional benefit from existing and soon-to-be-launched, international magnetospheric and ionospheric missions to provide long-term continuous, synergistic and important contextual measurements as well as CAL/VAL, including SMILE (specifically the auroral imager) and Swarm missions within ESA and the JAXA FACTORS mission.**

Response: NASA concurs with this recommendation as part of a larger strategic approach, as discussed in the response to Recommendation 8. These types of collaborations have been a part of previous and on-going discussions with inter-agency and international partners, and NASA intends to continue in that manner.



Geospace Dynamics Constellation (GDC) Independent Review Board (IRB) Report

Co-Chair - O. Figue roa
Co-Chair - M. Hagan

Table of Contents

GDC Background

- The Geospace Dynamics Constellation (GDC) is a strategic, Living With a Star (LWS) mission that will accomplish breakthroughs in the fundamental understanding of processes that govern the dynamics of the Earth's upper atmosphere which surrounds and protects the planet
- The goals of GDC are to reveal how the high latitude ionosphere-thermosphere (IT) system responds to variable external forcing by the solar wind and magnetosphere, and how internal processes in the global IT system redistribute mass, momentum, and energy
- The GDC was recommended in the 2013 Decadal Survey, "Solar and Space Physics: A Science for a Technological Society" as a strategic LWS mission (and reinforced in the mid term review)
- The GDC constellation will provide unprecedented measurements of the IT system on local, regional, and global scales and will inform space situational awareness and space weather prediction models

Introduction

- The NASA Science Mission Directorate Associate Administrator (SMD/AA) convened an IRB for the GDC mission to independently review whether the overall architecture and technical concept developed during Pre-Phase A is robust from a science, technical, and programmatic perspective
- GDC was approved to proceed into formulation in September 2020 as a strategic mission within the NASA/SMD Heliophysics Division (HPD) LWS Program
- Investigations and Interdisciplinary Science Teams (IDSs) selections were in progress at the start of the IRB and remain in progress
- The IRB conducted the assessment over ~ three months, relying upon IRB plenary sessions, IRB sub panels , interviews, attendance at community meetings, and one-on-one interviews with Project personnel and other key stakeholders

GDC IRB Members

Orlando Figueroa (Co-Chair)
Maura Hagan (Co-Chair)
Steven Battel
David Bearden
Anthea Coster
James Crocker
Ann Devereaux (SRB Chair)
Andrew Driesman
Jennifer Gannon

Shea Kearns (Review Manager)
Tara Roberts (Review Manager)

Richard Howard
Mark Jacobs
Justin Kasper
Jens Oberheide
Nicholas Pedatella
Dorothy Perkins
Jonathan Rae
Steven Thibault
Olga Verkhoglyadova

Executive Summary – 1 of 2

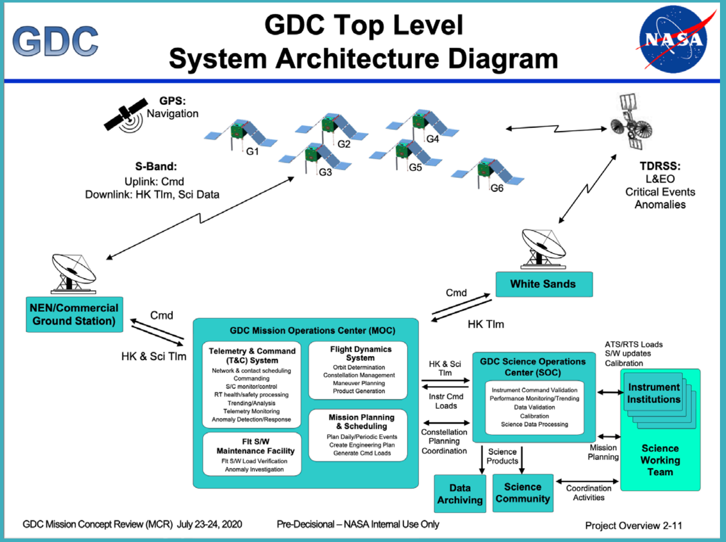
- The mission architecture, selected and planned investigations/instrumentation, and the concept of operations proposed for GDC will address the primary 2013 Decadal Survey recommendations
- Unprecedented GDC observations will enhance understanding of prevailing space weather conditions in the ionosphere-thermosphere (IT) system and lead to improvements in IT models that are foundational to space situational awareness and space weather prediction
- The GDC mission is strongly supported by the heliophysics community and the community of stakeholders
- The current NASA FY23 budget and profile does not support a Launch Readiness Date (LRD) of 2029/30; it delays the LRD to 2032 or later at additional cost, and exposes NASA to uncertainty and risks
- An LRD of 2029/30 (Project Estimate to Complete (ETC) Aug/2029) is credible for a mission of the scope and nature of GDC, but additional funding on the order of $200-$300M is likely required
- GDC is challenged by production of 6 spacecraft/6 identical set of instruments with unique requirements; concerted efforts are necessary to address supply and production planning, and strategies to simplify spacecraft/instrument interface requirements and deliverables

Executive Summary – 2 of 2

- GDC offers a unique opportunity for NASA to document and apply lessons learned from the GDC Project's approach to pre-formulation, formulation, and implementation for application to future constellation architecture endeavors
- The influence of atmospheric wave forcing from below on the IT system as envisioned in the 2013 Decadal Survey is unaddressed by GDC, stressing the need for concurrent measurements by other missions
  - There is also great community interest in concurrent observations to address the forcing from below from a mission like DYNAMIC
- Communication with the heliophysics community about GDC status and decisions has been constrained, which the IRB attributes to overly strict adherence to process and interpretation of policies and regulations by NASA, and that permeated and negatively impacted the Science Technology Definition Team (STDT), the Announcement of Opportunity (AO) process, and the interfaces with the Project
- Efforts to educate and engage a more diverse community through workshops (e.g., early career scientists, HPD Helio2050 science planning workshop) are noteworthy and should be expanded, along with efforts to educate the general public about GDC

GDC Architecture

- Baseline mission: Six spacecraft (6 identical sets of instruments) in different inclinations 81-82 degrees/400Km orbits, differential procession separates the orbit planes as they precess in local time
  - Important to launch 6 S/C to protect the integrity of the minimum required (5) to meet science objectives in 3 years
- Threshold mission: Four spacecraft address highest priority science objectives in the STDT



GDC

GDC Top Level System Architecture Diagram

GPS: Navigation

G1 G2 G3 G4 G5 G6

S-Band:
Uplink: Cmd
Downlink: HK Tlm, Sci Data

TDRSS:
L&EO
Critical Events
Anomalies

NEN/Commercial Ground Station)

Cmd

HK & Sci Tlm

White Sands

Cmd

HK Tlm

GDC Mission Operations Center (MOC)

Telemetry & Command (T&C) System
Network & contact scheduling
Commanding
S/C monitor/control
RT health/safety processing
Trending/Analysis
Telemetry Monitoring
Anomaly Detection/Response

Flight Dynamics System
Orbit Determination
Constellation Management
Maneuver Planning
Product Generation

Flt S/W Maintenance Facility
Flt S/W Load Verification
Anomaly Investigation

Mission Planning & Scheduling
Plan Daily/Periodic Events
Create Engineering Plan
Generate Cmd Loads

HK & Sci Tlm

Instr Cmd Loads

Constellation Planning Coordination

GDC Science Operations Center (SOC)
Instrument Command Validation
Performance Monitoring/Trending
Data Validation
Calibration
Science Data Processing

ATS/RTS Loads
S/W updates
Calibration

Instrument Institutions

Mission Planning

Science Working Team

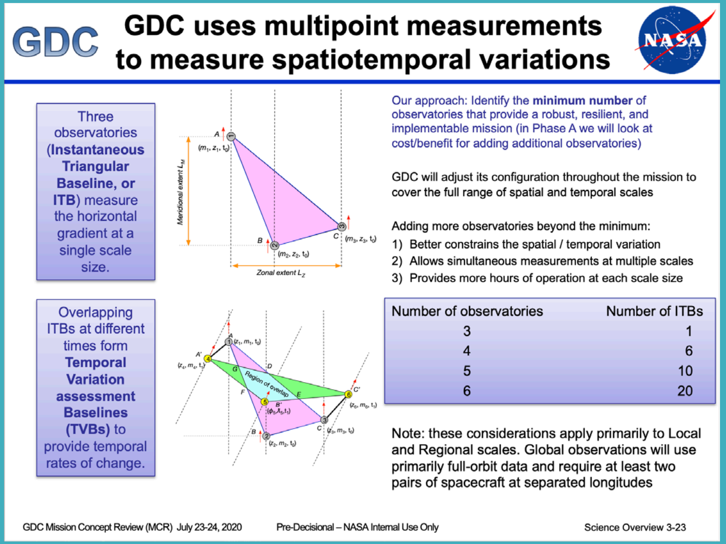
Science Products

Data Archiving

Science Community

Coordination Activities

GDC Mission Concept Review (MCR) July 23-24, 2020 Pre-Decisional – NASA Internal Use Only Project Overview 2-11



GDC

GDC uses multipoint measurements to measure spatiotemporal variations

Three observatories (**Instantaneous Triangular Baseline, or ITB**) measure the horizontal gradient at a single scale size.

Our approach: Identify the **minimum number** of observatories that provide a robust, resilient, and implementable mission (in Phase A we will look at cost/benefit for adding additional observatories)

GDC will adjust its configuration throughout the mission to cover the full range of spatial and temporal scales

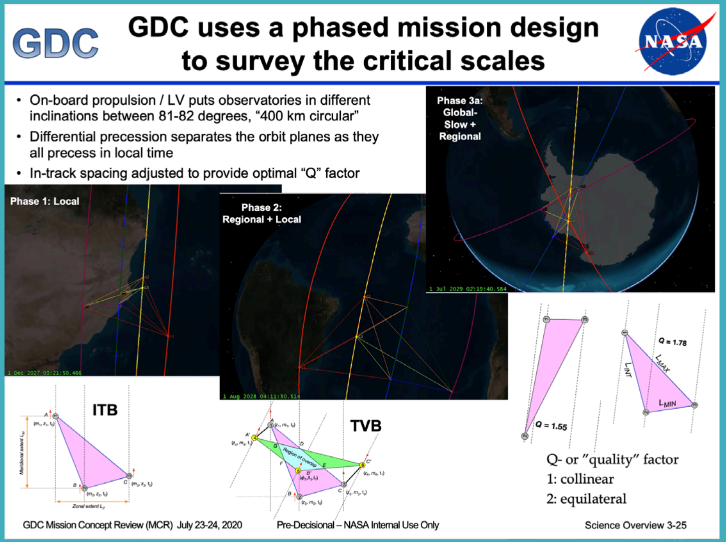
Adding more observatories beyond the minimum:
1) Better constrains the spatial / temporal variation
2) Allows simultaneous measurements at multiple scales
3) Provides more hours of operation at each scale size

Overlapping ITBs at different times form **Temporal Variation assessment Baselines (TVBs)** to provide temporal rates of change.

Number of observatories	Number of ITBs
3	1
4	6
5	10
6	20

Note: these considerations apply primarily to Local and Regional scales. Global observations will use primarily full-orbit data and require at least two pairs of spacecraft at separated longitudes

GDC Mission Concept Review (MCR) July 23-24, 2020 Pre-Decisional – NASA Internal Use Only Science Overview 3-23



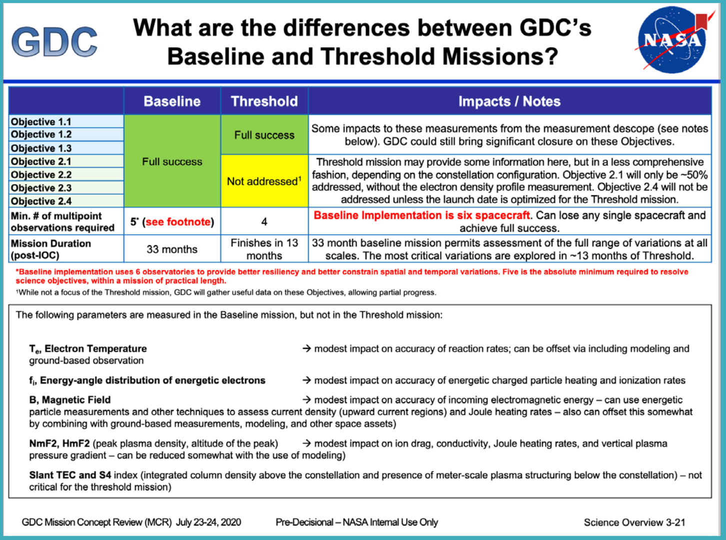
GDC

GDC uses a phased mission design to survey the critical scales

- On-board propulsion / LV puts observatories in different inclinations between 81-82 degrees, "400 km circular"
- Differential precession separates the orbit planes as they all precess in local time
- In-track spacing adjusted to provide optimal "Q" factor

Q- or "quality" factor
1: collinear
2: equilateral

GDC Mission Concept Review (MCR) July 23-24, 2020 Pre-Decisional – NASA Internal Use Only Science Overview 3-25



GDC

What are the differences between GDC's Baseline and Threshold Missions?

	Baseline	Threshold	Impacts / Notes
Objective 1.1 Objective 1.2 Objective 1.3	Full success	Full success	Some impacts to these measurements from the measurement descope (see notes below). GDC could still bring significant closure on these Objectives.
Objective 2.1 Objective 2.2 Objective 2.3 Objective 2.4		Not addressed[1]	Threshold mission may provide some information here, but in a less comprehensive fashion, depending on the constellation configuration. Objective 2.1 will only be ~50% addressed, without the electron density profile measurement. Objective 2.4 will not be addressed unless the launch date is optimized for the Threshold mission.
Min. # of multipoint observations required	5* (see footnote)	4	**Baseline Implementation is six spacecraft**. Can lose any single spacecraft and achieve full success.
Mission Duration (post-IOC)	33 months	Finishes in 13 months	33 month baseline mission permits assessment of the full range of variations at all scales. The most critical variations are explored in ~13 months of Threshold.

***Baseline implementation uses 6 observatories to provide better resiliency and better constrain spatial and temporal variations. Five is the absolute minimum required to resolve science objectives, within a mission of practical length.**

[1] While not a focus of the Threshold mission, GDC will gather useful data on these Objectives, allowing partial progress.

The following parameters are measured in the Baseline mission, but not in the Threshold mission:

T_e, Electron Temperature → modest impact on accuracy of reaction rates; can be offset via including modeling and ground-based observation

f_i, Energy-angle distribution of energetic electrons → modest impact on accuracy of energetic charged particle heating and ionization rates

B, Magnetic Field → modest impact on accuracy of incoming electromagnetic energy – can use energetic particle measurements and other techniques to assess current density (upward current regions) and Joule heating rates – also can offset this somewhat by combining with ground-based measurements, modeling, and other space assets)

NmF2, HmF2 (peak plasma density, altitude of the peak) → modest impact on ion drag, conductivity, Joule heating rates, and vertical plasma pressure gradient – can be reduced somewhat with the use of modeling)

Slant TEC and S4 index (integrated column density above the constellation and presence of meter-scale plasma structuring below the constellation) – not critical for the threshold mission)

GDC Mission Concept Review (MCR) July 23-24, 2020 Pre-Decisional – NASA Internal Use Only Science Overview 3-21

GDC Investigations/Instruments

AO Selections - to Date

- Modular Spectrometer for Atmosphere and Ionosphere Characterization (MoSAIC) - Principal Investigator: Dr. Mehdi Benna UMBC/GSFC
- Atmospheric Electrodynamics probe for THERmal Plasma (AETHER) – Principal Investigator: Dr. Laila Andersson LASP/U of CO
- Comprehensive Auroral Precipitation Experiment (CAPE) – Principal Investigator: Dr. Daniel Gershman GSFC

AO Selections - Pending

- Thermal Plasma instrument to provide information about energy of ions and electrons; MoSAIC measures total ion and electron density
- Magnetometer

Others (TBD)

- Radio Occultation, Dosimeter

MoSAIC

Modular Spectrometer for Atmosphere and Ionosphere Characterization

A Geospace Dynamics Constellation (GDC) Proposal
Submitted in Response to
2021 GDC Instrument PEA NNH17ZDA0040-GDC

Principal Investigator:
Dr. Mehdi Benna
Center for Space Science and Technology
University of Maryland, Baltimore County

September 22, 2021

Principal Investigator
Dr. Daniel Gershman
NASA Goddard Space Flight Center

Comprehensive Auroral Precipitation Experiment

CAPE

A Geospace Dynamics Constellation (GDC) Instrument
Proposal Submitted in Response to PEA
NNH17ZDA0040-GDC

September 22, 2021

Principal Investigator
Dr. Daniel Gershman
NASA Goddard Space Flight Center

Authorizing Official
Deborah Amato
Chief New Opportunities Office
NASA Goddard Space Flight Center

Atmospheric Electrodynamics
probe for THERmal plasma

AETHER

An Investigation of the Ionosphere
and Thermosphere

Dr. Laila Andersson
Principal Investigator
Laboratory for Atmospheric
and Space Physics
University of Colorado

Randy S. Siders
Executive Associate Director
Finance and Operations
Laboratory for Atmospheric
and Space Physics
University of Colorado

Terms Of Reference (TOR)

1. Are the scope and cost/schedule understood and properly aligned?
   a. What is the likely range of probable cost and schedule, and what are the drivers?
   b. How do non-optimal funding profiles affect the cost/schedule of the mission, and what is the impact of staying within the funding profile guidelines?

2. Is the management approach and structure adequate for a project of this scope and complexity?
   a. Do the acquisition strategy and subsequent procurements have sufficient focus and oversight to ensure the delivery of high-quality products on cost and within schedule?

3. Are the GDC science team and the planned collaborations structured and focused to maximize the return on NASA's investment, both scientifically and for potential contributions to National interests?
   a. Are the suggested real-time Space Weather data transmission of significant value to the scientific community, other U.S. agencies, and/or our Space Industry including applications to topics of space weather (e.g. navigation/communication) and of space situational awareness (e.g. orbital debris)?
   b. Are there potential collaborations on or synergies with topics of scientific and National importance currently unexplored for GDC?

Terms Of Reference – Findings

Strengths of GDC

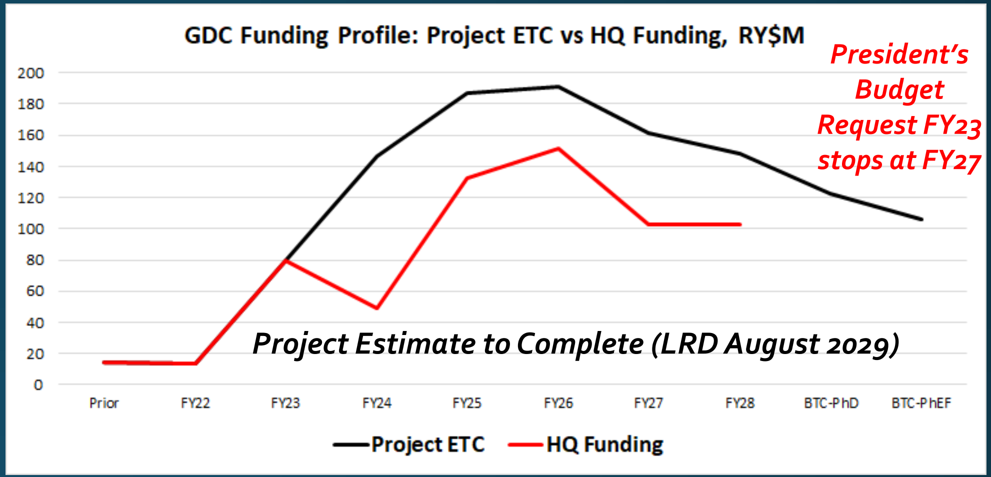
- The GDC Project benefits greatly from the management and technical support and assistance provided by the Explorers & Heliophysics Projects Division (EHPD) at NASA/Goddard Space Flight Center (GSFC)
- The GDC team has done a stellar job of thinking about the concept of operations (CONOPS) and science operations; they have identified mission phases, operating modes and a constellation management approach that puts science first, simplifies spacecraft operations, and adds robustness
- The GDC Project has been very responsive to requests for developing and providing budget and schedule details and iterations with HPD at NASA/SMD and was very open and responsive to IRB requests for similar and other requests
- The early “Request For Information” from spacecraft providers is a positive step to aid with early planning efforts
- The interdisciplinary science (IDS) teams are selected

Terms Of Reference – 1 of 3

1. Are the scope and cost/schedule understood and properly aligned?
   a. What is the likely range of probable cost and schedule, and what are the drivers?
   b. How do non-optimal funding profiles affect the cost/schedule of the mission, and what is the impact of staying within the funding profile guidelines?

TOR Question #1: Are the scope and cost/schedule understood and properly aligned?

- The IRB examined Project costs and schedule from multiple perspectives
  - Analysis of Project Estimates & HQ Funding
  - IRB Independent Cost Modeling
  - Analogy Comparisons



President's Budget Request FY23 stops at FY27

Project Estimate to Complete (LRD August 2029)

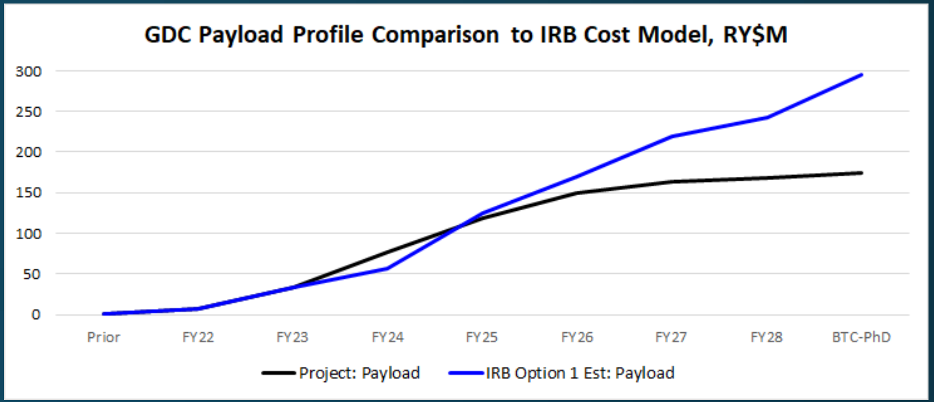
Note: Costs shown do not include HQ UFE

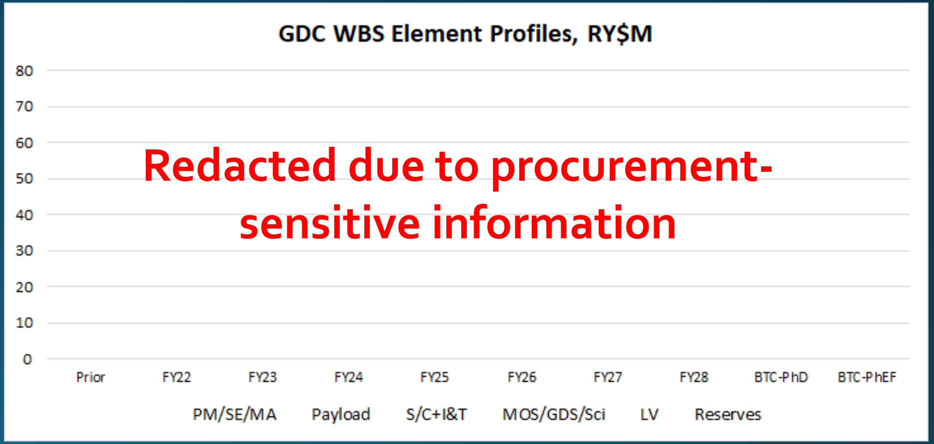
- The FY23 budget profile is not conducive to a credible Project plan
  - Limitations force the Project to artificially adjust plans to comply
  - FY24 reduction significantly handicaps Project's ability to effectively start
  - Delays the mission to 2032 LRD or later, with added risk and uncertainty

NOTE: All IRB cost analyses explore Project costs @ 50% confidence level and do not include HQ UFE

TOR Question #1: Are the scope and cost/schedule understood and properly aligned?

- Payload costs appear underestimated and ramp down too early for the Aug 2029 LRD
- The planned early ramp up for the S/C and Payload is not achievable with current budget
  - FY24-28 deficiencies in $97-295M range
- The Project ETC ramp-downs for the S/C+I&T and Payload are unrealistic


GDC Payload Profile Comparison to IRB Cost Model, RY$M


GDC WBS Element Profiles, RY$M

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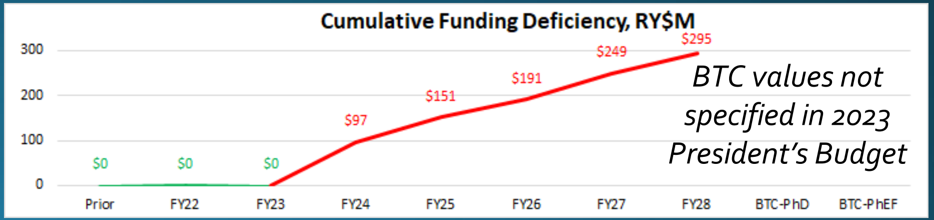
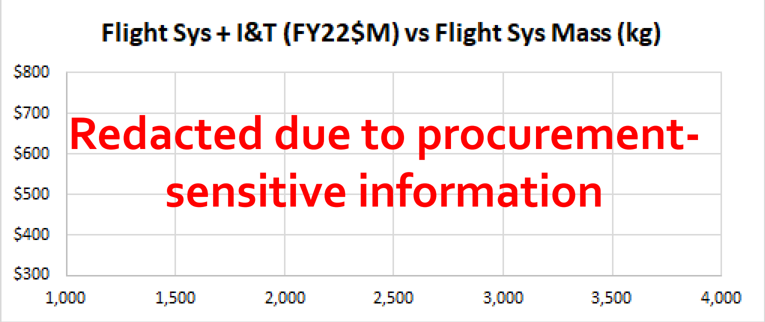

Cumulative Funding Deficiency, RY$M

BTC values not specified in 2023 President's Budget

TOR Question #1: Are the scope and cost/schedule understood and properly aligned?

- Comparison of IRB results to the Project ETC based on Phases B/C/D cost models
    - Project's Phase-A costs are $156M and run into FY24 but have too little time for Phase-B (only 9 months)
    - Phase-B is assumed to start in FY24 for model comparisons
- IRB estimates are significantly higher for the Payload, Science Team
- Analogy comparisons to VAP and MMS show a similar cost difference
    - Both analyses show a $200-300M underestimate

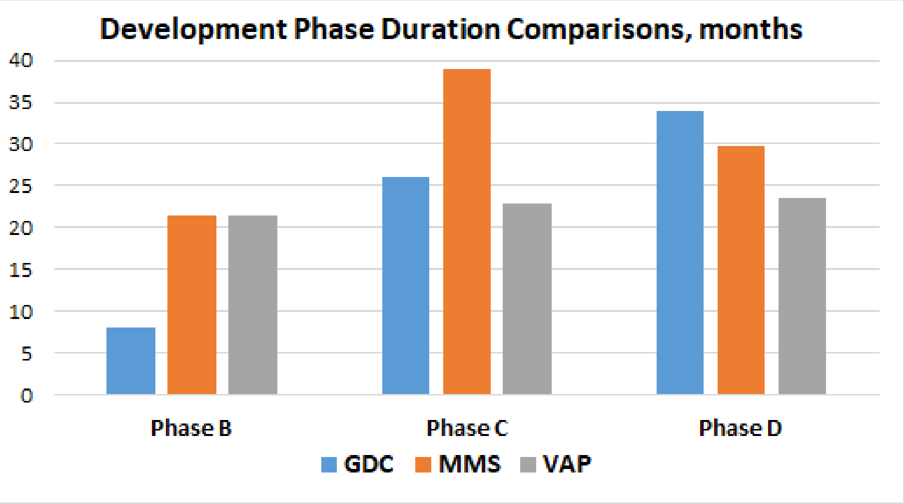
GDC IRB Cost Model Results			**Option 1**	
RY$M	*June 2022*	**Project ETC**	**IRB Bsln**	*Delta*
Phase A		**Redacted due to procurement sensitive information**	**107**	**Redacted due to procurement sensitive information**
Phases B-D				
1/2/3	PM/SE/MA		108	
4	Science Team		79	
7/9	MOS/GDS		41	
5	Payload		261	
6/10	S/C + I&T		303	
B-D Subtotal			**791**	
	B-D Reserves		237	
PHASE BCD TOTAL			**1,029**	
PHASE A-D TOTAL			**1,136**	
8	Launch Service		**145**	
PHASE EF TOTAL			**106**	
PHASE A-F TOTAL			**1,387**	


Flight Sys + I&T (FY22$M) vs Flight Sys Mass (kg)

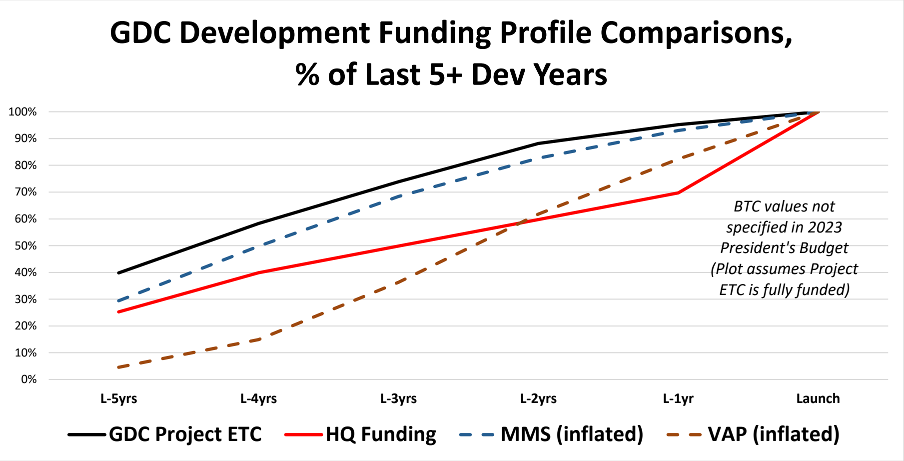
Redacted due to procurement-sensitive information

TOR Question #1: Are the scope and cost/schedule understood and properly aligned?

- Life Cycle Phases A-C need revisiting
    - GDC Phase-B is unrealistically short
- The HQ Funding profile provides insufficient early funding to support development of six flight units
    - More early funding is used as the number of flight units increases from VAP (2) to MMS (4)
    - Project ETC estimated profile appears more realistic but likely not sufficient to support six units
- GDC schedule adjustments are needed to comply with available HQ Funding



Development Phase Duration Comparisons, months

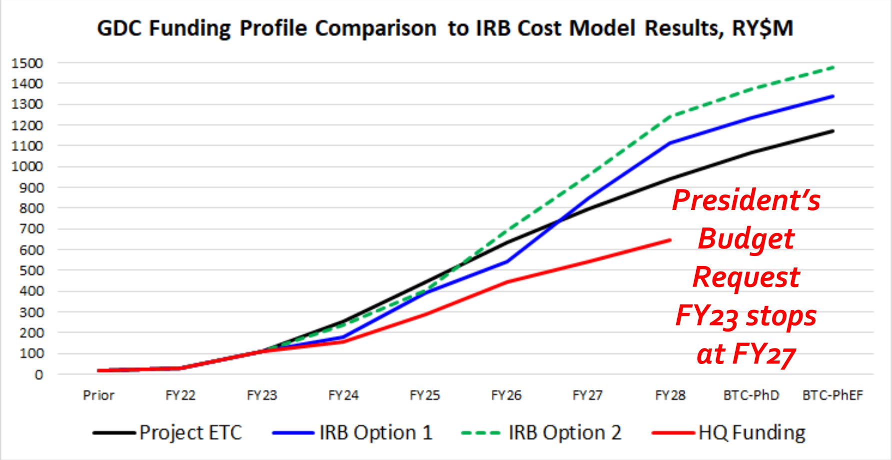


GDC Development Funding Profile Comparisons, % of Last 5+ Dev Years

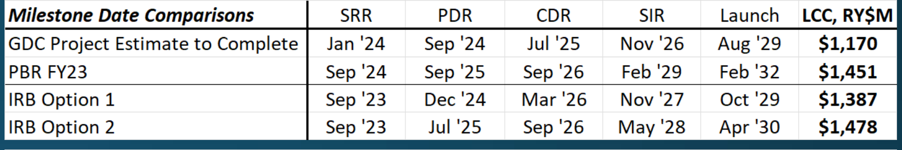
BTC values not specified in 2023 President's Budget (Plot assumes Project ETC is fully funded)

TOR Question #1: Are the scope and cost/schedule understood and properly aligned?

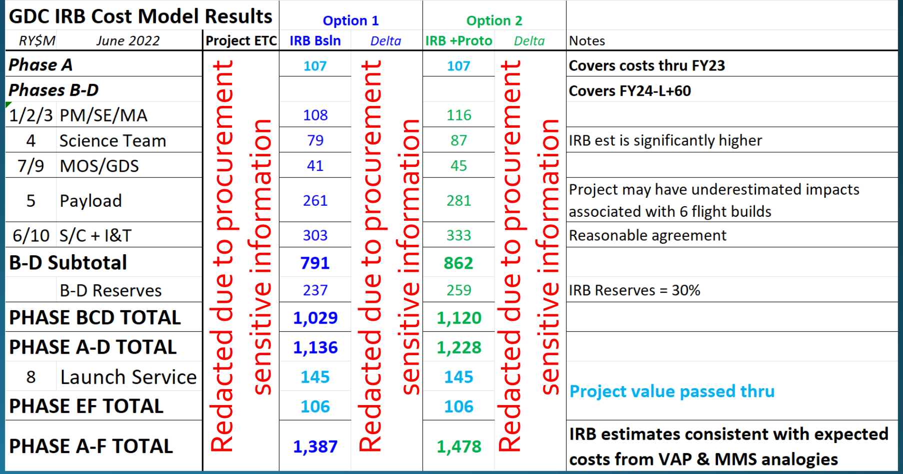
- The IRB explored an “Option 2” to develop an Engineering Unit/Prototype (S/C and instruments) by CDR to help refine the system design (*See Table*)
  - Address risks associated with non-recurring engineering, multiple production, supply chain, and instrument accommodation
  - Engineering Unit turned to Protoflight 6th S/C for flight
- Adds to early funding needs but reduces risk
  - Adds ~$100M to the IRB cost model estimate and moves the LRD out by ~6 months
- Enables a better informed Key Decision Point (KDP)-C and reduces risks on Project and HQ UFE in later stages


GDC Funding Profile Comparison to IRB Cost Model Results, RY$M

President’s Budget Request FY23 stops at FY27



Milestone Date Comparisons	SRR	PDR	CDR	SIR	Launch	LCC, RY$M
GDC Project Estimate to Complete	Jan '24	Sep '24	Jul '25	Nov '26	Aug '29	**$1,170**
PBR FY23	Sep '24	Sep '25	Sep '26	Feb '29	Feb '32	**$1,451**
IRB Option 1	Sep '23	Dec '24	Mar '26	Nov '27	Oct '29	**$1,387**
IRB Option 2	Sep '23	Jul '25	Sep '26	May '28	Apr '30	**$1,478**



GDC IRB Cost Model Results		**Option 1**		**Option 2**		
RY$M *June 2022*	**Project ETC**	**IRB Bsln**	*Delta*	**IRB +Proto**	*Delta*	Notes
Phase A	Redacted due to procurement sensitive information	107	Redacted due to procurement sensitive information	107	Redacted due to procurement sensitive information	**Covers costs thru FY23**
Phases B-D						**Covers FY24-L+60**
1/2/3 PM/SE/MA		108		116		
4 Science Team		79		87		IRB est is significantly higher
7/9 MOS/GDS		41		45		
5 Payload		261		281		Project may have underestimated impacts associated with 6 flight builds
6/10 S/C + I&T		303		333		Reasonable agreement
B-D Subtotal		**791**		**862**		
B-D Reserves		237		259		IRB Reserves = 30%
PHASE BCD TOTAL		**1,029**		**1,120**		
PHASE A-D TOTAL		**1,136**		**1,228**		
8 Launch Service		**145**		**145**		**Project value passed thru**
PHASE EF TOTAL		**106**		**106**		
PHASE A-F TOTAL		**1,387**		**1,478**		**IRB estimates consistent with expected costs from VAP & MMS analogies**

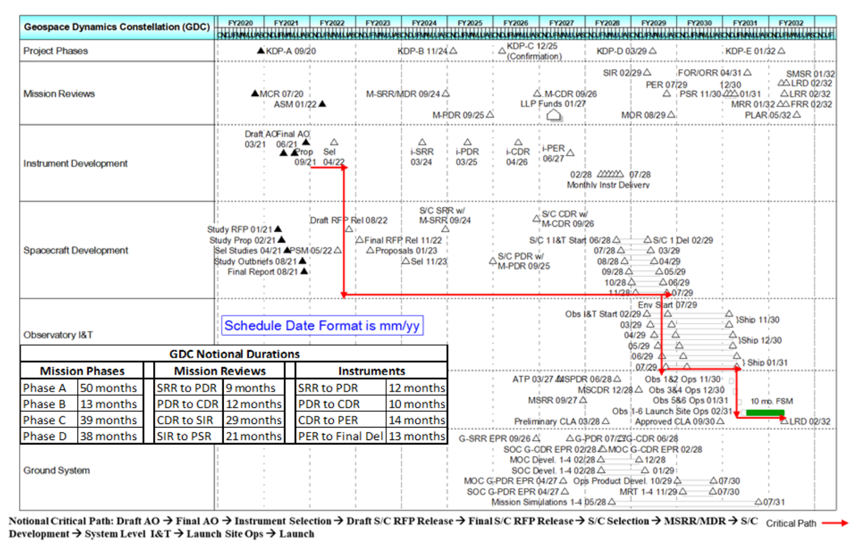
TOR Question #1: Are the scope and cost/schedule understood and properly aligned?

- The Project provided limited information about their President's Budget Request (PBR) FY23 scenario
- Many schedule inefficiencies are applied to meet funding profile requirements
  - Extending Phase-A to over four years
  - Low budget profile during fabrication extends schedule negating possible savings from multiple units
- More detail regarding the underlying PBR FY23 assumptions is needed to support a credible IRB assessment, and the IRB questions the basis for estimates

Project Plan (PBR FY23)

WBS		Phase A	Phase B	Phase C/D	Phase E	Phase F	Grand Total
1.0	Project Management						
2.0	Systems Engineering						
3.0	Safety & Mission Assur.						
4.0	Science						
5.0	Payload						
6.0	Spacecraft						
7.0	Mission Operations						
9.0	Ground Systems						
10.0	Systems Integ. & Testing						
Subtotal							
Contingency Total							
Subtotal GSFC Only							
11.1	Public Outreach						
11.2	Student Collaboration						
8.0	Launch Vehicle						
Total GSFC/LV/Suballottments							
HQ's UFE							
Total Mission							

Redacted due to procurement-sensitive information



GDC Notional Durations					
Mission Phases		**Mission Reviews**		**Instruments**	
Phase A	50 months	SRR to PDR	9 months	SRR to PDR	12 months
Phase B	13 months	PDR to CDR	12 months	PDR to CDR	10 months
Phase C	39 months	CDR to SIR	29 months	CDR to PER	14 months
Phase D	38 months	SIR to PSR	21 months	PER to Final Del	13 months

Notional Critical Path: Draft AO → Final AO → Instrument Selection → Draft S/C RFP Release → Final S/C RFP Release → S/C Selection → MSRR/MDR → S/C Development → System Level I&T → Launch Site Ops → Launch

Milestone Date Comparisons	SRR	PDR	CDR	SIR	Launch	**LCC, RY$M**
GDC Project Estimate to Complete	Jan '24	Sep '24	Jul '25	Nov '26	Aug '29	**$1,170**
PBR FY23	Sep '24	Sep '25	Sep '26	Feb '29	Feb '32	**$1,451**

Terms Of Reference – 2 of 3

2. Is the management approach and structure adequate for a project of this scope and complexity?
    a. Do the acquisition strategy and subsequent procurements have sufficient focus and oversight to ensure the delivery of high-quality products on cost and within schedule?

TOR Question #2: Is the management approach and structure adequate for the scope and complexity?

- The Project organization is typical with very experienced key personnel identified, but not clear who is responsible for the system level/global view for the integration of plans to face the challenges associated with multiple copies
  - Planning, supply chain, logistics, production and integration of instrument by institutions that may be unaccustomed to operate under such demands
  - Many high voltage power supplies, each with long lead parts (e.g., transformers and/or optocouplers, accelerated lifetime test requirements, etc.)
- The level of coordination and volume of work required to meet the mission needs for a 2029/2030 LRD will place high demands in procurement/contracts personnel support to meet the schedule plans and options at GSFC and elsewhere
- In general, staffing to support instruments and spacecraft efforts will place high demands on the Project and GSFC

TOR Question #2: Is the management approach and structure adequate for the scope and complexity?

- There are significant accommodation expectations associated with the instruments that will challenge providers of “production” or “off-the-shelf” spacecraft buses (e.g., EMI/C Requirements, Mag and electrostatic cleanliness, purge, contamination control)
  - Providers have experience and expectations that accommodations will be made to maximize science return and may underbid
  - Spacecraft providers will try to leverage constellation/production capabilities to reduce cost
  - Likely to increase system complexity resulting in increased costs, longer schedules and/or compromises in science measurements
- With six+ copies of instruments and complex accommodations, payload system engineering is a significant challenge in need for a different approach to payload system engineering
  - Payload system engineers typically deal with integrating a single payload onto a single bus assuring programmatic and technical success
  - Science instrument providers do not have recent experience fabricating and testing relatively large numbers of instruments and subassemblies

TOR Question #2: Is the management approach and structure adequate for the scope and complexity?

- Phase-A is excessively long, while nine months for Phase-B is aggressive to mature the preliminary design for compliance (or compromise) on the reference mission requirements
  - The plans do not seem to take advantage of the line experience from providers that can adapt to production and to a somewhat compressed Phase C/D by negotiating requirements to take advantage of their capabilities
- Integration and test schedule for builds of six+ instruments are overly aggressive and will be a strain on limited resources
  - Production strategies for instruments vary but they all assume aggressive fabrication and I&T phases
  - These are likely not realizable given the lack of recent experience and other industry-wide issues, such as management of multiple concurrent activities

TOR Question #2: Is the management approach and structure adequate for the scope and complexity?

- The KDP-A decision memo did not include the mission risk classification agreement between the parties, and the Formulation Authorization Document (FAD) is ambiguous in this regard, stating that the mission is "envisioned as a Class C"
  - Signed Mission Assurance Requirements (MAR) includes Class "B" upgrades (e.g., EEE Parts) without the benefit of an in-depth risk assessment
  - Risk classification is important in that it will drive decisions at multiple levels (e.g., Mandatory Inspections, Decision making review boards, EEE Parts, PCB Boards, radiation, etc.) with cost and schedule implications
  - The IRB is concerned that the mindset of architecture level redundancy, and the natural tendencies to upgrade at the spacecraft level will close the door to more programmatically and technically effective solutions

Terms Of Reference – 3 of 3

3. Are the GDC science team and the planned collaborations structured and focused to maximize the return on NASA's investment, both scientifically and for potential contributions to National interests?
    a. Are the suggested real-time Space Weather data transmission of significant value to the scientific community, other U.S. agencies, and/or our Space Industry including applications to topics of space weather (e.g. navigation/communication) and of space situational awareness (e.g. orbital debris)?
    b. Are there potential collaborations on or synergies with topics of scientific and National importance currently unexplored for GDC?

TOR Question #3: Are the GDC science team and the planned collaborations structured and focused to maximize return on investment?

- The mission architecture and concept of operations proposed for GDC address the 2013 Decadal Survey recommendations for the notional reference mission, pending final investigation/instrument selections, with the notable exception of the effects of atmospheric wave forcing from below
  - The GDC constellation will provide unprecedented measurements of the IT system on local, regional, and global scales with six identical spacecraft providing simultaneous multi-point observations
  - Concurrent operations of a mission like DYNAMIC would address the shortfall and increase the return on NASA's investment beyond the individual GDC and DYNAMIC missions

TOR Question #3: Are the GDC science team and the planned collaborations structured and focused to maximize return on investment?

- NASA's overly strict adherence to process, interpretation of policies and regulations, inability to adopt recognized best practices from past STDT efforts, and inadequate planning for inclusivity, negatively impacted the communication and community support efforts required for GDC success
    - NASA established the STDT under the Federal Advisory Committee Act (FACA) and was managed in an unnecessarily constrained fashion limiting communications with the community
    - During the early stages of GDC formulation, NASA neglected to both brief the community about progress and plans, and to demonstrate strong and enthusiastic support for the mission
    - Some questions and issues raised by community members in response to the draft GDC investigation/instrument AO were not acknowledged, addressed, or publicly archived on the GDC acquisition homepage
- Notwithstanding the GDC mission is of critical importance and NASA can establish a sustained path to overcome these challenges

TOR Question #3: Are the GDC science team and the planned collaborations structured and focused to maximize return on investment?

- The mission has been in a protracted transition period, leading to confusion in the community about Roles, Accountability, Authority (RAA), while the Program Scientist is managing the open AO for the selection of the remaining GDC investigations/instruments
  - The IRB applauds the July 2022 selection of the Project Scientist and Deputies that were added to support the effort; delays in these formal appointments had a negative impact in cementing the Project Scientist role as a leader and advocate for the mission science with the community
- Communication with the heliophysics community about mission status and decisions was to date sparse and disturbingly constrained, including during the June 2022 CEDAR and GEM community workshops
  - Community members who were not in attendance at those workshops remain largely uninformed about the GDC mission status

TOR Question #3: Are the GDC science team and the planned collaborations structured and focused to maximize return on investment?

Science Team Structure

- The early addition of the IDS teams was critically important to GDC and is now enabling efforts to meld individual instrument team science investigations in pursuit of cohesive mission and constellation objectives during GDC formulation
  - The IDS teams also complement and extend the expertise and capabilities of the GSFC Project Scientist team and add diversity to its membership

TOR Question #3: Are the GDC science team and the planned collaborations structured and focused to maximize return on investment?

Importance of GDC real-time data to space weather stakeholders

- NOAA NWS/SWPC , which holds the federal mandate for space weather operations, wrote a strong letter of support for GDC
- GDC data streams can be ingested into NOAA NESDIS/OPPA data pipelines, expanding infrastructure to support future NOAA-NASA collaborations
- Space weather disturbances occur throughout the solar cycle, as evidenced by the loss of 40 Starlink satellites worth ~$100M during minor storm (i.e., G1) conditions only a day after they were launched in February 2022. GDC will provide valuable real-time observations when launched during any phase of the solar cycle
- Despite operational stakeholders' (i.e., NOAA NESDIS/OPPA, NOAA NWS/SWPC, Space Force, Air Force, Navy) expressed support for GDC real-time data, it remains unclear which organization will incorporate these data streams into *operational* models

TOR Question #3: Are the GDC science team and the planned collaborations structured and focused to maximize return on investment?

Importance of GDC to space weather stakeholders

- Unprecedented GDC observations will lead to improvements in state-of-the-art IT models which are foundational to space situational awareness and space weather prediction
  - GDC will facilitate improvements to current operational models, and the processes that drive space weather disturbances therein, including representations of thermospheric expansion (that leads to increased atmospheric drag on satellites), ionospheric irregularities, and high latitude aurora
  - GDC will provide opportunities to assimilate unique geophysical data into R2O models, allowing assessment of predictive capabilities for future operational use. NOAA NWS/SWPC's WAM-IPE is one example of such a model that is of top National priority for space weather

TOR Question #3: Are the GDC science team and the planned collaborations structured and focused to maximize return on investment?

Importance of GDC to space weather stakeholders

- Unprecedented GDC observations will lead to improvements in state-of-the-art IT models which are foundational to space situational awareness and space weather prediction *(continued)*
  - Updates and extensions to observation-based climatological models of the IT will offer higher spatial and temporal resolution with the inclusion of GDC measurements.
  - Assimilation of GDC data into first-principle global circulation models of the IT system will provide exceptional new opportunities to explore the underlying physical processes governing the IT response and recovery to space weather events, while assessing the hindcast capabilities of these models

TOR Question #3: Are the GDC science team and the planned collaborations structured and focused to maximize return on investment?

Potential collaborations or synergies with topics of scientific and National importance

- The GDC mission is of crucial importance to US National interests, warranting urgent attention
  - US industry and government agencies have billions of dollars invested in technologies that society relies on orbiting in IT space, and US society increasingly relies upon these assets
  - GDC science is foundational to understanding prevailing space weather conditions in the IT system, along with the system's response to disturbances and extreme events, that often lead to orbital decay and potential satellite loss, communication and navigation degradation or losses, and radiation exposure to humans in space, among others

TOR Question #3: Are the GDC science team and the planned collaborations structured and focused to maximize return on investment?

Potential collaborations or synergies with topics of scientific and National importance

- The GDC mission is of crucial importance to US National interests, warranting urgent attention *(continued)*
  - It is unclear whether there is common understanding (i.e., among commercial stakeholders, the general public, and elected officials) of the extant and increasing vulnerability of space assets and the urgent need to fill IT system knowledge gaps aimed at enhancing space weather forecast capabilities in support of their preservation
  - The IRB is concerned that pressures on the HPD budget drive decisions that compromise strategic Heliophysics flagship missions that address the recommendations of the Decadal Surveys
  - NASA and the heliophysics community have yet to pursue strong and broad advocacy for a fully-funded robust and timely GDC mission in partnership with agencies and commercial stakeholders

TOR Question #3: Are the GDC science team and the planned collaborations structured and focused to maximize return on investment?

Potential collaborations or synergies with topics of scientific and National importance

- The GDC mission is of crucial importance to US National interests, warranting urgent attention *(continued)*
  - GDC will rely on ground-based (GB) measurements (e.g., ISRs and FPIs) to calibrate and validate GDC measurements; adding high-temporal resolution IT diagnostics from these same GB facilities would extend the GDC science return at mesoscales
  - DARPA (Ref. April 2022 Technical Announcement for Ouija) seeks to deploy a constellation of eight spacecraft in a 200-300 km orbit to provide real-time information on ionospheric HF radio propagation via HF receiver, GPS radio occultation, and in-situ Langmuir probe measurements; areas of strong synergies with GDC science.

TOR Question #3: Are the GDC science team and the planned collaborations structured and focused to maximize return on investment?

Synergies and potential GDC collaborations with international partners worth pursuing

- Potential European Space Agency (ESA) collaborations may include, but are not limited to, hosted payloads, additional spacecraft and GB support
- There are existing and soon-to-be-launched international magnetospheric and ionospheric missions such as the Swarm and SMILE missions within ESA and the JAXA FACTORS mission
- The synergistic scientific interests of the international ground-based community, and EISCAT 3D in particular, may include magnetosphere-ionosphere-thermosphere coupling processes as well as opportunities for GDC Calibration/Validation over the Arctic

Recommendations

Recommendations – 1 of 5

1. The GDC budget (total and yearly profile) needs to be corrected to be better aligned with plans, correct deficiencies identified, and to assign the proper UFE at the Project and NASA/SMD level
2. A system level optimization approach should be undertaken by the Project in the very near future to steer the plans for formulation and implementation towards global system level optimization and solutions, including designating a lead position whose job is to focus on the issues of supply chain, logistics, and production
   - A probabilistic risk assessment to inform trades for implementation of the Class C risk classification (e.g., Level 2 versus Level 3 parts, selective redundancy, etc.) is urged
   - Define the trade space for instrument requirements against the spacecraft provider offerings so that there is clear understanding from the beginning
3. The Project should aggressively address risks associated with non-recurring engineering, multiple unit production, supply chain, interfaces and instrument accommodation to reduce risk during the non-recurring phase, such as:
   - Develop a fully integrated engineering unit (S/C and instruments) of sufficient fidelity to be upgradable to protoflight as 6th S/C for flight
   - Downselect a suitable spacecraft/SI&T provider from two candidate in a two-step process
   - Explore other approaches designed to reduce the burden of the effort

Recommendations – 2 of 5

4. Life Cycle phases should be revisited to allow for the early development of the engineering unit S/C provider 2-step selection process
5. Consistent with the guidance and intent of the 2013 Heliophysics Decadal survey and the mid-term assessment, NASA SMD, HPD, and the GDC Project should proactively advocate for GDC and its critical contributions to the Heliophysics System Observatory (HSO) within the science and stakeholder communities
6. The leadership of the Project Scientist team should be empowered to speak authoritatively about GDC and assume prime responsibility for interactions with the community and science performance trades that enable cost effective system level solutions; RAA of the Project Scientist versus that of the Program Scientist need to be clear and unambiguous

Recommendations – 3 of 5

7. NASA should develop a strategy in close collaboration with NSF and other national and international GB facility operators for GB measurements (e.g., ISRs and FPIs) to calibrate and validate GDC measurements
8. NASA should undertake a valuation exercise to assess the capability of the suite of simultaneous GDC, DYNAMIC like, and GB observations, and to calculate the extent to which the collective contributions exceed the sum of individual element contributions
   - The exercise should include the development of complementary aspirational budgets to quantify the cost of maximizing the return on the collection of GDC, DYNAMIC like, and GB investments

Recommendations – 4 of 5

9. NASA should capture lessons learned and revisit the approach for interactions and engagement with the heliophysics community for missions in the early stages, particularly strategic missions
    - The approach for GDC was unnecessarily constrained, and eroded confidence in the plans and motivations
    - Mission plans, definition, and early formulation processes should be open and transparent with the community to every extent possible
    - Best practices for the conduct of an STDT (or equivalent) process should be captured and normalized across NASA/SMD in the form of a handbook
10. Much stronger collaboration between NASA and other agencies, including NOAA NESDIS/OPPA, NOAA NWS/SWPC, Space Force, Air Force, and the Navy, and DARPA as well as commercial stakeholders is urged to understand and proactively address space weather impacts on space assets and to develop plans to incorporate GDC data streams into operational models; coordination with NOAA NWS/SWPC which holds the federal mandate for space weather operations, is particularly encouraged

Recommendations - 5 of 5

11. Given the international interest in the science that GDC will address, NASA should investigate *plausible future collaboration* with international partners, such as ESA, to augment and extend GDC science
    - Collaborations could include, instruments, hosted payloads, additional spacecraft and GB support
12. NASA should investigate the additional benefit from *existing and soon-to-be-launched*, international magnetospheric and ionospheric missions to provide long-term continuous, synergistic and important contextual measurements as well as CAL/VAL, including SMILE (specifically the auroral imager) and Swarm missions within ESA and the JAXA FACTORS mission

Other Observations – 1 of 2

- The progress achieved by HPD in addressing the 2013 Decadal Survey recommendations over the last decade is noteworthy
- The selection of investigations/instruments from multiple and varied organizations (e.g., GSFC, Universities, other institutions) may create unintentional inequities in access and turnaround times for resources, support, and response to actions; the GDC Project should be proactive in assuring the same opportunities to GSFC and non-GSFC investigation teams so that they are treated equitably and as full members of the GDC team
- GDC offers a unique opportunity for a new approach to constellation architectures of the future, NASA should take advantage of that possibility to find new and strategic approaches to formulation and implementation
- An IRB, when performing independent cost, schedule and risk estimates at this early stage, fills a gap to better inform KDP-A and how NASA approaches the formulation of assigned (i.e., not competed) missions

Other Observations – 2 of 2

- A more diverse NASA science community will set the stage for the success of future missions and programs. NASA SMD and HPD should continue and expand ongoing efforts to reach out to, educate, train, and develop more diversity in the broader science community and in heliophysics, starting with GDC
- Increased efforts are needed by NASA/HPD to demonstrate the importance of the science of GDC and other HPD missions
  - There is limited information, video, images, etc. to communicate with and engage the general public and stakeholders on the importance and benefits of the science in a way that is factual, accessible, and engaging

Summary and Conclusions – 1 of 2

- The GDC mission addresses the primary 2013 Decadal Survey recommendations
- GDC science is foundational to understanding prevailing IT space weather conditions and the system’s response to extreme space weather events, that often lead to potential satellite loss, communication and navigation degradation or losses, and radiation exposure to humans in space
- The GDC mission is supported strongly by the heliophysics community and the broader national community of stakeholders
- The IRB examined Project costs and schedule from multiple perspectives and concludes that:
  - An LRD of 2029/2030 is credible for a mission of the scope and nature of GDC; the current President's profile and budget do not support this LRD
  - The Project Baseline Plan requires additional $200-$300M for a 2029/2030 LRD

Summary and Conclusions – 2 of 2

- Concerted efforts are necessary to specifically address the GDC challenges associated with supply and production planning, economies of scale, and strategies to simplify spacecraft/instrument interface requirements and deliverables
- Communication with the heliophysics community about GDC mission status and decisions has been constrained and must be improved
- NASA should evaluate the capability of a project suite, involving GDC, a mission that characterizes dynamical forcing from below, and GB observations of the IT to determine if the collective contributions exceed the sum of individual parts
  - International agreements may offer opportunities to address some needs
- Collaborations between the NASA GDC team and interested operational space weather partners, including NOAA NESDIS/OPPA, NOAA NWS/SWPC, Space Force, Air Force, and the Navy, warrant improvement, particularly for coordination with NOAA NWS/SWPC, which has the federal mandate for space weather operations

Appendix

Acronyms

AO – Announcement of Opportunity

AETHER – Atmospheric Electrodynamics probe for THERmal Plasma

BTC – Budget to Complete

CAPE – Comprehensive Auroral Precipitation Experiment

CEDAR – Coupling, Energetics and Dynamics of Atmospheric Regions

DARPA – Defense Advanced Research Projects Agency

EEE – Electrical, Electronic, Electromechanical

EHPD – Explorers & Heliophysics Projects Division

EMC – Electro Magnetic Compatibility

EMI – Electro Magnetic Interference

ESA – European Space Agency

ETC – Estimate to Complete

FAD – Formulation Authorization Document

FPIs – Fabry-Perot Interferometers

GB – Ground Based

GDC – Geospace Dynamics Constellation

GEM – Geospace Environmental Modeling

GSFC – Goddard Space Flight Center

HPD – Heliophysics Division

HSO – Heliophysics System Observatory

HQ – Headquarters (NASA)

IDS – Interdisciplinary Science Teams

IRB – Independent Review Board

ISRs – Incoherent Scatter Radars

IT – Ionosphere/Thermosphere

Acronyms Continued

KDP – Key Decision Point

LRD – Launch Readiness Date

LWS – Living With a Star

MAR – Mission Assurance Requirements

MCP – Micro Channel Plates

MMS – Magnetospheric Multiscale

MoSAIC – Modular Spectrometer for Atmosphere and Ionosphere Characterization

NASA – National Aeronautics and Space Administration

NESDIS – National Environmental Satellite, Data, and Information Service

NOAA – National Oceanic and Atmospheric Administration

NWS – National Weather Service

OPPA – Office of Projects, Planning, and Analysis

PCB – Printed Circuit Board

R2O – Research to Operations

RAA – Roles, Accountability, Authority

SMD – Science Mission Directorate

STDT – Science and Technology Definition Team

SWPC – Space Weather Prediction Center

TOR – Terms Of Reference

VAP – Van Allen Probes

WAM-IPE – Whole Atmosphere Model-Ionosphere Plasmasphere Electrodynamics