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Geospace Dynamics Constellation Design Reference Mission: Predicted Ephemeris Description

GDC GSFC CMO

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Goddard Space Flight Center
Greenbelt, Maryland

National Aeronautics and Space Administration

Geospace Dynamics Constellation

Design Reference Mission: Predicted Ephemeris Description

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Preface

This document is a Geospace Dynamics Constellation (GDC) Project configuration control board (CCB) controlled document. Changes to this document require prior approval of the GDC CCB Chairperson or designee. Proposed changes shall be submitted in the GDC Technical Data Management System (TDMS) via a configuration change request (CCR) along with supportive material justifying the proposed change. Changes to this document will be made by complete revision.

All requirements in this document are designated by the word "shall" unless otherwise stated.

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Change History Log

Note: Document began at Revision A. There is no Revision -. Revisions A and B were never submitted to TDMS for review and are NOT CM Released.

Revision	Effective Date	Description of Changes
A	Sept 14, 2020	First public release
B	Jan 7, 2021	Updated timestamps on graphics to days since launch instead of date. Corrected minor typos. No substantive changes to this document from Rev A. Accompanying movies and figures in ephemeris data file distribution have been updated to remove date timestamps, using days since launch instead. No substantive changes were made in the content of the data files, movies, or graphics in the distribution.
C	July 5, 2022	Updated ephemeris specification to reflect latest "baselined" ephemerides. These are designed to satisfy updated requirements for Temporal Variation assessment Baseline (TVB) coverage, as well as updated scale-size definitions. The new ephemeris specification results in a mission that provides significantly better coverage in the "baseline" configuration (six spacecraft) and is much more resilient against loss of any single spacecraft (while meeting baseline science requirements) or any two spacecraft (while meeting threshold science requirements). In addition, this ephemeris specification will expand the range of possible launch days in each year so that GDC can launch on any, or nearly any day, and still meet its science requirements, even after a loss of one (baseline) or two (threshold) spacecraft. These ephemerides have been through significant testing, both with a flight dynamics prototyping tool, and with high-fidelity predicted ephemerides. Explicitly defined Virtual Sampling Baselines (VSBs) and "Virtual TVBs" as well as generalized Q factor for N-gon sampling geometries. Added notes on sampling philosophy and explicitly defined TVB "validity" and "counting" constraints. Released per GDC-CCR-0055

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1 INTRODUCTION

1.1 Purpose

This document presents the mission phases, constellation configuration, and predicted ephemerides for the Geospace Dynamics Constellation's (GDC) "Design Reference Mission" (DRM). GDC's DRM is the plan for configuring the orbits of a set of six (6) GDC observatories in order to gather the observations necessary to achieve its Science Objectives. The DRM is based on high-fidelity flight dynamics simulations (see **Section 2.1** for limitations and assumptions) and represents a mission sequence that is well within the capability of typical spacecraft bus designs.

The DRM was originally developed as part of GDC pre-formulation activities, and in support of the instrument Announcement of Opportunity (AO). Version B of this DRM (dated Jan 7, 2021) was the definitive version for the instrument AO. Since the instrument AO was released, further refinement of the constellation configuration and evolution has continued, resulting in Version C of the DRM (described by this document). This has had a primary focus on ensuring that GDC has solid margins on all science requirements for coverage (*e.g.,* hours per scale/local time/season bin), and good robustness of the constellation's ability to cover all scales, local times, seasons, and latitudes independent of GDC's launch date. These updates have also focused on making the constellation sampling more symmetric so that any single observatory can be lost and still enable GDC to meet its baseline science objectives.

Further constellation refinement is planned in Phase A/B, although it is expected that changes to the constellation will be optimizations rather than significant deviations from this DRM.

This document includes:

- A description of the guiding principles and assumptions used in developing the DRM
- A description of the sampling scheme assumed in developing the DRM
- Listing of each mission phase and detailed aspects of sampling and constellation architecture during these phases
- A description of the format and contents of the predicted ephemeris files that accompany this document.

1.2 Scope

This document and the associated ephemeris files are publicly available and can be downloaded directly from https://ccmc.gsfc.nasa.gov/missionsupport/GDC_support.php. This document and the associated ephemeris files are configuration managed as a unit by the GDC Project.

This document and the described ephemeris are provided for planning purposes. They are not intended to state or imply any requirements for GDC. In the case of contradiction between this document and any document containing requirements for the GDC project, those documents supersede this document.

1.3 Related Documentation

1.1.1 Reference Documents

- NASA Science and Technology Definition Team for the Geospace Dynamics Constellation Final Report https://science.nasa.gov/files/science-red/s3fs-public/atoms/files/GDC%20STDT%20Report%20FINAL.pdf

- Proposal Information Package for the Geospace Dynamics Constellation Announcement of Opportunity (https://lws.larc.nasa.gov/pdf_files/GDC-PYLD-DESC-0002%20Rev%20C_1509773.pdf)

2 GENERAL

2.1 DRM Guiding Principles and Assumptions

The GDC DRM represents the current baseline sampling and constellation evolution approach to gather the observations required to meet GDC's Science Objectives. It is an evolution and refinement of the approach that was assessed during the Mission Concept Review and Key Decision Point-A (KDP-A) reviews and the Revision B approach which was in effect at the time of the SALMON-3 PEA ("GDC Instrument AO"). The DRM was developed with the following top-level principles in mind:

1) The DRM was developed as a constellation consisting of **six identical observatories** to address the GDC Science Objectives.

2) The DRM was designed to provide sampling at all spatiotemporal scales outlined in the GDC Science and Technology Definition Team (STDT) report (local, regional, and global scales). Where possible, observations suitable for studying cross-scale coupling, and/or multiple overlapping measurements at different spatial baselines, are also included to strongly constrain system dynamics.

3) The DRM was designed to gather data for sufficient time at each scale/local time/season. The STDT report stressed the necessity for gathering local and regional data at multiple local times and local, regional, and global data over the full range of seasons, including separately for two solstice seasons to fully address GDC Science Objective 2.4 about hemispheric asymmetries (which was Objective 2.6 in the STDT).

4) The DRM was designed to gather data over as much of the globe (geographic latitude and geomagnetic latitude) as practical to fulfill GDC's Science Objectives addressing global processes and dynamics.

5) The DRM was designed to prioritize a dense set of observations in a narrow altitude band (350-400 km). This serves the following purposes:
    a. Minimizes variation in measured neutral pressure that are purely due to observations being made at different altitudes. This limits variations to a fraction of a scale height at any given latitude.
    b. Permits measurement of nearly all the magnetospheric energy inputs to the upper atmosphere.
    c. Minimizes drag impacts to maximize mission duration.
    d. Keeps the GDC constellation as close to the altitudinal region of maximum ionosphere-thermosphere coupling as possible, in a region where vertical shears in neutral wind and vertical gradients in temperature are expected to be small
    e. Maintains frequent access to low-latitude measurements near and below the nighttime F-peak

6) The DRM was designed to be robustly implementable, minimizing propellant requirements and maneuver cadence, maximizing the duty cycle with which individual observatories are making science measurements, and providing resiliency against a partial loss of the constellation. Implementation details include realistic plans for collision avoidance and a maneuver schedule that is infrequent enough to permit long uninterrupted gathering of science data.

7) The DRM was designed as a "phased" mission, with different intervals during the mission focusing on measurements at different scale sizes, allowing the most efficient use of a relatively small number of observatories. The phases defined in the DRM provide a complete sampling of the most important spatial and temporal scales outlined in the STDT and serve as a guide to the general types of constellation sampling configurations that can readily be achieved.

8) The DRM's predicted ephemerides were developed as a high-fidelity simulation that accounts for nearly all the significant orbital perturbations, but they did not include drag effects. GDC is designed to keep the observatories in a narrow range of altitudes (see above) and the constellation is re-boosted to an apogee of 400 km every time drag brings perigee down to 350 km (which is expected to occur every few months). This is not reflected in the DRM ephemeris data, but it is accounted for in the mission design associated with the DRM (*e.g.,* in the anticipated delta-v requirement for orbit re-boosting). The actual altitude variation is not expected to strongly impact the constellation configuration, as the simulated ephemeris include maneuvers to keep the constellation at the specified spacings and altitudes within reasonable tolerances. For more details, see **Section 2.3**.

2.1.1. Basic Sampling Scheme

One of the most critical aspects of the GDC mission is that, to answer its Science Objectives, it provides the **first systematic and quantitative measurement survey of spatial and temporal variations** of the energy inputs into the upper atmosphere **as well as of the dynamical and chemical responses of the neutral and ionized gases** that comprise it.

Measuring spatial variations can provide, for example:

1) Direct measurements of gradients, *e.g.,* pressure gradients which accelerate neutral winds (GDC Objectives 1.1, 2.1, and 2.3)
2) Much more accurate assessment of spatially-integrated heating rates that drive changes in neutral density (GDC Objective 1.3)
3) Much more accurate assessment / constraints on bulk motion / convection patterns that drive changes in plasma and neutral density (GDC Objectives 1.2 and 1.3)
4) Assessment of hemispheric asymmetries (GDC Objective 2.4)
5) Assessment of wavelength, propagation speed, etc. for Traveling Atmospheric Disturbances (TADs) and Traveling Ionospheric Disturbances (TIDs) (GDC Objective 2.2)

Similarly, measuring temporal variations is required, for example, to:

1) Correlate forcing (*e.g.,* pressure gradients, ion drag) with the observed accelerations (*e.g.,* the neutral wind) to discriminate between physical mechanisms
2) Correlate heating rates (*e.g.,* Joule, particle precipitation) with the observed temperature changes
3) Better constraints on the motion of individual parcels of ionized or neutral gas as they move under time-varying convection.

In the GDC observing region specified in the STDT (300-400 km), there are both vertical and horizontal gradients of critical physical parameters that characterize driving / energy inputs and atmospheric responses. The vertical gradients can, with certain exceptions, either be directly measured by remote sensing, or be accurately estimated from suitably comprehensive measurements of state parameters in a narrow altitude range. Horizontal gradients of some parameters of interest to GDC can be measured using imaging / remote sensing techniques, but other parameters cannot, and thus require a different approach – multipoint direct sampling *in situ*.

This leads to the basic sampling scheme outlined in the GDC STDT – *a number of observatories, configured as a constellation with sampling baselines commensurate with the gradient scale sizes of interest to a particular science investigation, and with "revisit times" appropriate to the temporal rates of change under study.*

2.1.1. Philosophy of sampling scheme and development of figures of merit

What follows is a description of a system the GDC Project team has developed that represents "figures of merit" for defining, describing, and evaluating a range of possible sampling geometries and evolutions for the GDC constellation. The various concepts defined here are meant to conceptually represent, in a simple and intuitive way, the configurations of the observatories as they sample the local space environment, and how GDC will combine these measurements to estimate two-dimensional gradients and temporal rates of change.

In reality, naïvely calculating the gradients using finite differences in this way would produce large uncertainties and noise in the gradient and rate-of-change measurements, so the actual analysis schemes will depend on a host of more advanced techniques such as Least Squares Gradient Calculation with Adaptive Scaling (LSGC-AS) [*de Keyser et al., 2007; de Keyser, 2008*], Spherical Cap Harmonic Analysis [*Fiori et al., 2013; Fiori et al., 2014*], Spherical Elementary Current Systems [*Vanhamäki and Juusola, 2020*], and others, which use more robust fitting and optimization techniques, as well as data assimilative modeling [see, *e.g., Matsuo, 2020*] to appropriately combine data from multiple observatories taken over a set of locations in space-time.

Nonetheless, to develop requirements for the constellation evolution, and to optimize the DRM, it was necessary to utilize simple "counting" schemes whereby we could define approximate geometries that work well with those more advanced schemes, and which could be used to evaluate a range of possible schemes for the constellation evolution.

Thus, the GDC Level 1 requirements will be written in terms of, for example, the number of hours of observations in a "bin" defined by certain ranges of local time, season, spatiotemporal scale, and in some cases latitude. To determine how well a given GDC constellation evolution meets those requirements, the Project developed predicted ephemerides, and then counted the number of times that particular spatiotemporal configurations of observatories occur. The requirements are written in language that denotes, for example, the number of hours that contain sampling configurations that meet certain geometric requirements. But it is always important to keep in mind that ultimately the performance of the mission will be assessed using more advanced fitting and optimization tools that can most optimally combine measurements spread in space-time to obtain accurate estimates of gradients and rates of change.

2.1.2. Instantaneous Triangular Baselines (ITBs)

To measure horizontal gradients, **at least** three measurement points are needed, all in close altitudinal proximity, sampling close together in time compared to the rates of change under study, and with an appropriate separation in latitude and longitude. Intuitively, any set of three spacecraft can be thought of as providing an *"instantaneous triangular baseline" (ITB)* with baseline separations that are commensurate with the gradient scale sizes under study. **Figure 1** shows an example of an ITB formed by three (presumed homogeneously instrumented) observatories, with a zonal ("cross-track") baseline of length L_Z and a meridional ("in-track") baseline of length L_M.

To directly measure vertical gradients, at least one additional measurement point separated vertically by a length appropriate to the gradient would be needed. However, in the GDC observing region, many parameters (*e.g.,* horizontal neutral wind, neutral temperature) have only weak vertical gradients, or vertical gradients that can be readily estimated from local measurements (*e.g.,* neutral density and composition, high-latitude quasistatic electric field). Given the significant complexity introduced, addition of measurements at multiple altitudes was not deemed to be of significant value to most of the science objectives outlined in the STDT. The most notable exception is plasma density, which can have strong and variable vertical gradients, where transport and finite lifetime effects can make direct estimation based on local measurements more difficult. This makes the capability to perform remote sensing of vertical profiles of plasma density (at least enough to constrain the ionospheric peak) a useful consideration in the design of the GDC mission.

The GDC sampling scheme focuses on measurements of horizontal gradients using groups of three or more observation points separated in latitude and longitude (i.e., not collinear), but closely spaced in altitude.

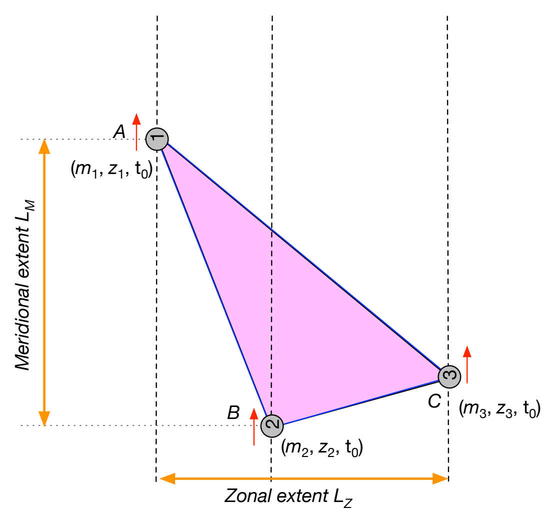

Figure 1-- Any three coplanar but non-collinear observatories, forming an Instantaneous Triangular Baseline, or ITB, can be used to measure the instantaneous average value of a parameter and its meridional and zonal gradients within a triangular region ABC.

This approach is most relevant for **local-scale and regional-scale** phenomena, where a gradient can be meaningfully computed.

2.1.3. Temporal Variation assessment Baselines (TVBs)

In order to measure temporal rates of change, GDC must "resample" the same region at two different times. This can be done, for "fast" variations, by following an ITB comprised of a set of three spacecraft in their orbit track and making observations during a time interval where the observatories move a corresponding distance (at orbital velocities near 8 km/s), so long as the time interval is short enough that there is sufficient overlap in the region sampled by the two ITBs. The resulting pair of spatially overlapping ITBs, taken at two different times, is referred to in the DRM as a *"temporal variation assessment baseline", or TVB*. This particular type of TVB is called a "*self-TVB*" for convenience.

TVBs can also be formed by ITBs which are independent and use different observatories (or only partially share observatories) and which sample the same spatial region at two different times, as the constellation evolves with the orbital motion of the observatories. These second types of TVBs, called "*cross-TVBs*", have the potential to explore a wide range of time delays between samples (while the first type of TVB is limited to study relatively short time delays, set by the orbital velocity). **Figure 2** shows these two cases. TVBs can measure time variations in parameters with gradients are appropriate to their measurement baseline lengths. A TVB can be made up of two ITBs, two VSBs ("Virtual Sampling Baselines", see **Section 2.2.4**), or one VSB and one ITB.

Two ITBs (or VSBs) that combine to make a TVB will, in principle, make a sequence of TVBs, as the trailing (in time) ITB samples different portions of the space previously sampled by the leading TVB. For purposes of this DRM, we count this sequence as a **single TVB, defined as the TVB that corresponds** to the moment of **maximum areal overlap** between the component ITBs or VSBs. We also assign the spatial scale, L, associated with the TVB to the square root of the overlap area at the time, **τ**, when the areal overlap is maximal. The time, **τ**, then is considered the

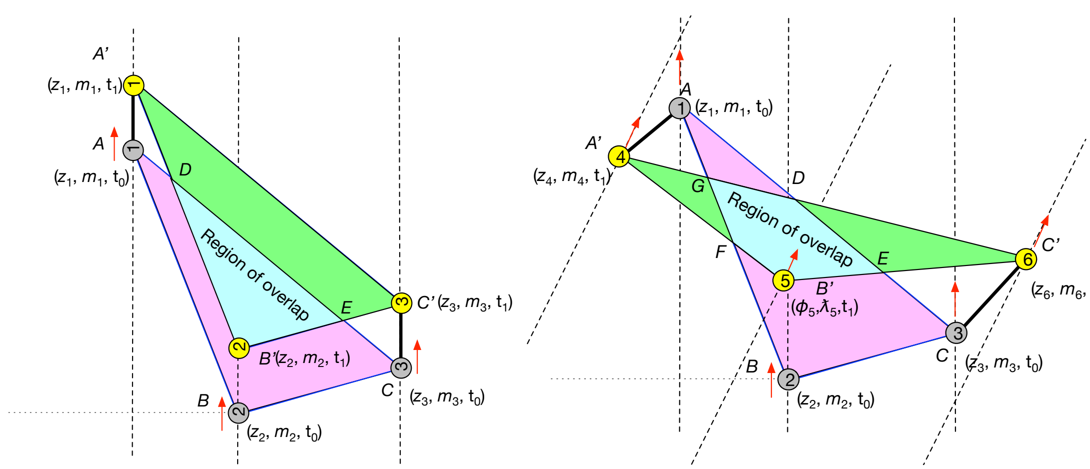

Figure 2-- Examples of TVBs: (left) Two subsequent, overlapping ITBs can be combined to form a Temporal Variation assessment Baseline (TVB), which can be used to measure the time variation in the average value of a parameter and its meridional and zonal gradient within a polygonal region A'C'CBA. Here, the region of overlap is DEB'. This situation is known as a "self-TVB"; (right): A more general example of a TVB, known as a "cross-TVB", forming the polygon ADC'CBFA', with region of overlap DEB'FG.

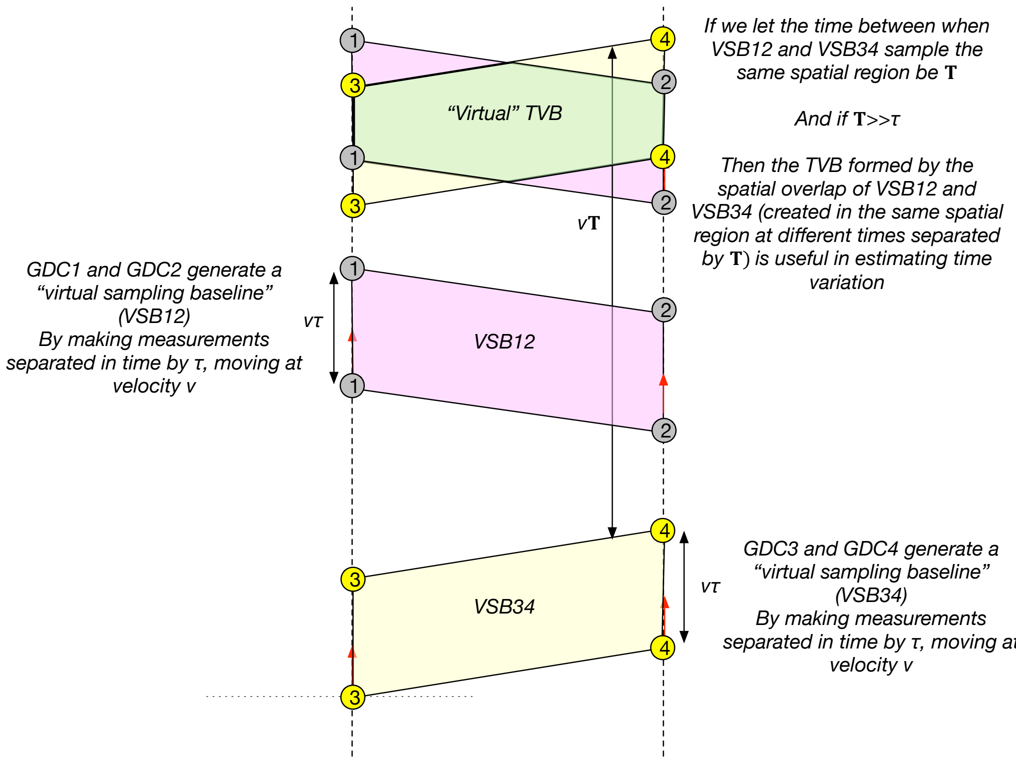

Figure 3-- Example of "Virtual" TVB formed by two pairs of spacecraft which can be used to measure time variations on scales long compared to the "formation time" of the virtual sampling baseline via orbital motion of the spacecraft. In practical situations, observatories 1 and 3 would not be in the same orbit plane, nor would observatories 2 and 4, in order to permit estimations of curvature error.

"temporal baseline" or "temporal scale" of the TVB. For self-ITBs, which are appropriate to local-fast and regional-fast scales, this will typically be the TVB at **τ** of 1 minute, since the overlap area will monotonically decrease with time.

2.1.4. Virtual TVBs and Virtual Sampling Baselines (VSBs)

Simultaneous spatial and temporal variations can be measured with fewer than six spacecraft under certain conditions, using the concept of "Virtual Sampling Baselines" (VSBs). A VSB can be made of a pair of spacecraft separated in the cross-track direction, as they sweep out / sample a certain distance in the in-track direction. **Figure 3** shows an example, in which there are four GDC spacecraft, comprising two VSBs, that together make a "Virtual" TVB. In this case, each pair of spacecraft is allowed to advance along its trajectory for a time ***τ*** that is short compared to the timescale of variation being sampled by the TVB. In this case, that timescale is given by **T,** the time the "trailing" VSB takes to occupy the same spatial region as the "leading" VSB. When the condition ***τ*** <<**T** is satisfied, then this approach can yield an assessment of the temporal variation on scales commensurate with **T.**

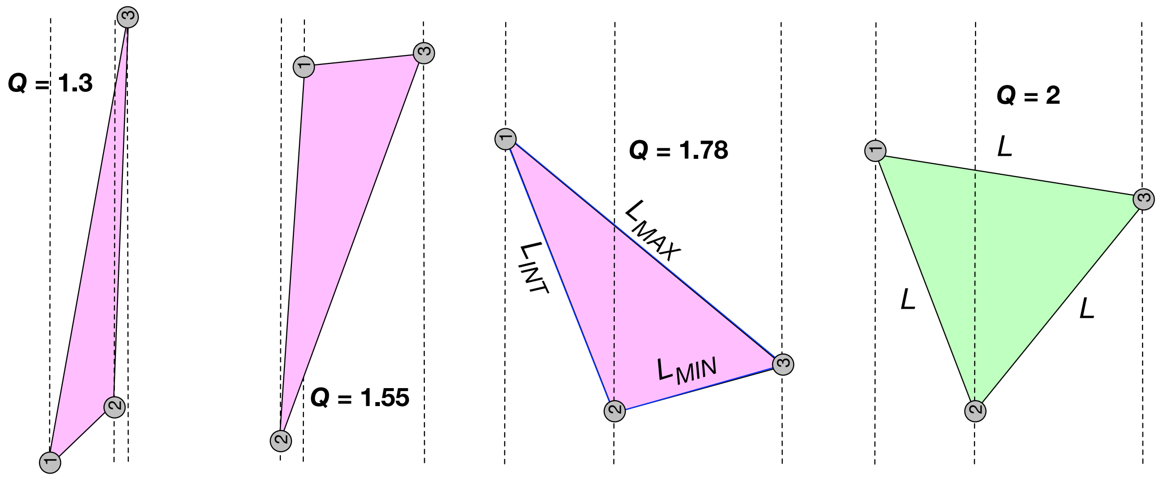

Figure 4 Examples of ITBs with different values of *Q*. Larger values of *Q* provide better estimations of average parameters and their horizontal gradients, in the isotropic case.

2.1.5. Sampling geometry and the *Q* factor

In the absence of *a priori* information about the gradient scales involved, and any zonal/meridional anisotropy (which may be large for certain types of features), error propagation analysis suggests that the ideal ITB geometry is one where the three observation points form an equilateral triangle (note: due to the spherical Earth and orbital dynamics considerations, individual ITBs are constantly deforming / evolving as the observatories move through their orbits). To perform a rough assessment of the measurement geometry for each ITB, the DRM defines a "Quality" or "*Q*" factor, shown in **Figure 4**.

Q is the ratio of the area subtended by the three vertices of the ITB (in spherical geometry) compared to the area that would be subtended by an equilateral spherical triangle of equal perimeter, as follows:

Let *a, b, c* be the arclength of the three sides of a spherical triangle, in radians.

Then the angles of the spherical triangle are *A, B, C*, given by:

$C = \mathrm{archav}((\mathrm{hav}(c) - \mathrm{hav}(a-b))/(\sin(a)*\sin(b))$
$A = \mathrm{archav}((\mathrm{hav}(a) - \mathrm{hav}(b-c))/(\sin(b)*\sin(c))$
$B = \mathrm{archav}((\mathrm{hav}(b) - \mathrm{hav}(c-a))/(\sin(c)*\sin(a))$

Where hav is the haversine function, $\mathrm{hav}(a) = \sin^2(a/2) = (1-\cos(a))/2$
And archav is the archaversine function $\mathrm{archav}(a) = 2*\sin^{-1}(\mathrm{sqrt}(a))$

Then the arclength of each side of an equilateral triangle with the same perimeter is *p*:

$p = (a+b+c)/3.$

And the three equal angles of this equilateral triangle are each:

P = archav((hav(p) – hav(0))/(sin(p)*sin(p))

And Q is given by 1 + the ratio of the triangle's area to the area of the equilateral triangle:

$Q = 1 + (A+B+C-\pi)/(3P-\pi)$

For VSBs, TVBs, or other sampling geometry, say an *N*-gon with *N* vertices, the definition of the *Q* factor can be generalized to the ratio of the area subtended by the *N* vertices of the *N*-gon (in spherical geometry) compared to the area that would be subtended by an equilateral spherical *N*-gon of equal perimeter.

Ideally (for optimal sampling of gradients whose direction can be at any angle to the satellite tracks), an ITB would form an equilateral triangle ($Q = 2$). The assumptions that permit estimation of parameters and their temporal variations and spatial gradients are broken when all three observatories in an ITB are collinear ($Q = 1$).

An important observation is that for N observatories, there are "N choose 3" possible ITBs that can be formed. For $N=6$, at any given time there are 20 ITBs, with varying baselines, coverage regions, and Q factors. The DRM is designed to try to optimize values of Q, over the full range of local and regional scales.

2.1.6. Other geometric constraints to ensure good sampling

In addition to the Q factor, we require several other conditions to be met, to more closely approximate ideal sampling geometries. All TVBs "counted" in each bin must satisfy the following additional constraints:

1) The Q factor for the component ITBs or VSBs that make up the TVB must be >=1.55. This is based on some initial empirical studies that trace the dependence of gradient error, using least-squares-fitting techniques, as a function of Q-factor.
2) The ratio of maximum ITB or VSB side length to minimum side length <= 4. There are some edge cases in which "long and skinny" spherical triangles can have good Q values, and this requirement tends to exclude them.
3) For a TVB to be valid, the component ITBs or VSBs must have an overlap that is at least 25% of the area of the larger of the two. The TVB is defined as that region of overlap.
4) A given TVB is judged to be at a certain "scale size" corresponding to a row in **Table 1** by taking its "spatial scale size" equal to the square root of the area of the TVB.
5) The component ITBs or VSBs that make up a TVB must have a maximum scale size (square root of area) ratio of 1.5. In other words, the larger one can have no more than 1.5x the scale size of the smaller (no more than 2.25x the area)

6) The component ITBs or VSBs must have center-to-center distance no larger than the scale-size of the smaller of the two ITBs
7) There is currently no requirement on "skewness", but this could be considered in future to further optimize sampling. Skewness is related to the cross-track spacing of the three spacecraft in an ITB and corresponds to how far "off center" the middle spacecraft of the three is from the halfway point between the easternmost and westernmost spacecraft. For certain reconstruction schemes, for example LSGC-AS, the assumption is that the gradient is uniform in the vicinity of the region sampled. Techniques of this type can return an estimate of the "curvature" error to understand when this assumption is broken to some extent. To do this well, they would need at least one set of samples in between the easternmost and westernmost samples to assess the degree of curvature error. In general, the accuracy in estimating curvature error may be expected to be maximized when the middle spacecraft is halfway between the other two. Certainly, if two of the spacecraft are in the same orbit track, there can be no estimate of the curvature error in the cross-track direction. This is an advantage of having the six spacecraft in different orbital planes.

2.1.7. Counting TVBs

For purposes of assessing how well the DRM provides data sufficient to address the GDC Science Objectives, the Project tabulated the TVBs according to the rules given above and assessed the number that occurred in each scale / season / local time / latitude bin. In this case, scale is one of "Local Fast", "Local Slow", "Regional Fast", or "Regional Slow" (see **Table 1**), season is "Northern Summer/Southern Winter", "Equinox", or "Southern Summer/Northern Winter", and local time is "Dawn", "Dusk", "Noon", or "Midnight". Both equinoxes are treated equivalently. Latitude bins are 10 degrees wide when assessing local scale phenomena and 20 degrees for regional-scale. While it can be quite valuable to have measurements from multiple TVBs at a given timestep in the same "bin" in order to better constrain spatial variations, the Project's assessment of the DRM performance counted only the first TVB in a given bin at each 30-second timestep, to ensure that GDC would get as much statistically independent data as possible. Then these counts were compared to other iterations of the DRM and to the Level 1 requirements for data sufficiency, to assess and optimize DRM performance.

2.1.8. Global-scale sampling

For **global-scale** measurements, the basic idea is similar – but instead of focusing on measuring average gradients between spacecraft, the goal of global-scale measurements is to more fully constrain and characterize the overall energy input and responses at all local times and latitudes. In this case, having observing points which are well spaced in local time, with local time gaps which are not "too large" will enable GDC to provide the first comprehensive characterization of upper atmospheric state and forcing on a global scale. The DRM achieves these global scale measurements with observatories that are appropriately distributed in local time, to get orbital and even sub-orbital time resolution on global-scale changes in this region. The Level 1 requirements also specify how many hours of global-scale data GDC must obtain under different seasons, and for each of the two "global" scales, "global-fast", and "global-slow". The DRM was assessed in terms of how many hours in each global scale / season bin, and this was an additional figure of

Mnemonic	Scale name	Scale size description	Spatial Scale[1], *L*	Temporal Scale[2], τ
LF	LOCAL-FAST	Local Scale, for rapid variations	300-3000 km	1-5 minutes
LS	LOCAL-SLOW	Local Scale, for slower variations	300-3000 km	>5 minutes
RF	REGIONAL-FAST	Regional Scale, for rapid variations	3000-9000 km	1-5 minutes
RS	REGIONAL-SLOW	Regional Scale, for slower variations	3000-9000 km	>5 minutes

[1]Spatial scale, *L*, is defined as the square root of the area of the TVB used for sampling.

[3]Temporal scale, τ, describes the range of temporal separations over which measurements must be made to provide an accurate enough assessment of rates of change. In principle, there is no upper bound, but in practice, designing a mission that samples a region *N* times per orbit will mean that anything greater than *1/N* of the orbital period (approx. 94 minutes at these altitudes) comes "for free" in any sampling architecture.

Table 1--Definition of local and regional scale sizes for the GDC DRM.

merit used to refine the DRM optimization and to ensure that the Level 1 requirements were met with margin.

2.2 General outline of the DRM

The STDT called out three spatial scale size regimes: "local", "regional", and "global". The DRM studies each of these scale sizes with a dedicated phase, as well as measurements of opportunity in other phases (*e.g.*, in Phase 3, the "global" phase, the constellation is often making "regional" scale measurements as well). The DRM then subdivides each of these into subphases corresponding to two temporal scales: "slow" (occurring on timescales of a few minutes up to an orbital period), and "fast" (occurring faster than a few minutes). **Table 1** and **Table 2** show the spatiotemporal scale definitions used in developing the DRM.

Phase	Start day	End day	LF	LS	RS	RF	GS	GF
1a	*91*	*162*						
1b	*163*	*195*						
2a	*196*	*336*						
2b	*337*	*476*						
3a	*477*	*616*						
3b	*617*	*756*						
4	*757*	*1095*						

Table 3 – The phases of the GDC DRM. For each phase, this table shows the day of mission (with day 1 being the launch day) for the start and end of that phase, as well as which scales are sampled during that phase (see Table 1 and Table 2 for scale definitions)

For the purposes of the DRM, the GDC launch date was chosen to be **May 1, 2028**. The actual GDC launch date is TBD pending further refinements of the GDC implementation. The GDC prime mission is three years, with a 33 month science phase following a 3-month long commissioning period (Launch and Early Orbit / Commissioning, or "LEOC").

The 36-month DRM is divided into several phases, which are listed in **Table 3** and detailed in **Section 2.5**. Note that days 1-90 consist of Phase 0 – Launch and Early Operations / Commissioning (LEOC), and on day 1095 the constellation will either go into an extended mission or de-orbit, at the determination of NASA HQ.

For purposes of the DRM, all six observatories in the GDC constellation (which are labeled G1, G2, …G6) are assumed to launch on a single launch vehicle. This launch vehicle inserts the observatories pairwise into three slightly different orbits, all approximately circular at 400 km altitude, with inclinations between 81 and 82.3 degrees. Propulsion systems on-board each observatory will be used to make slight adjustments to the orbit inclinations (putting all six observatories in orbits with slightly different inclinations), correct for launch vehicle dispersion, etc. **Table 4** shows the inclination of the orbits of the six observatories throughout the mission.

Scale	Scale name	Scale size description	Sampling Definition
GS	GLOBAL-SLOW	Global Scale, for slower variations	4 or more distinct orbit planes, LTAN spacing between westernmost and easternmost plane >=4.5 hours. No LTAN gap > 6 hours, maximum in-track phase difference between 4 spacecraft in these planes <= 30 minutes
GF	GLOBAL-FAST	Global Scale, for more rapid variations	4 or more distinct orbit planes, LTAN spacing between one pair of orbits 3-10 hours. LTAN spacing between a second independent pair of orbits 3-10 hours. Difference in mean LTAN of the two pairs <= the larger of [4 hours and half of the smaller of the two pairs' LTAN spans]. Within a pair, <= 20 minute in-track phase difference. Between pairs, >= 25 minute in-track phase difference between the mean time of each pair crossing the ascending node

Table 2-- Definitions relevant to global scale sampling for GDC.

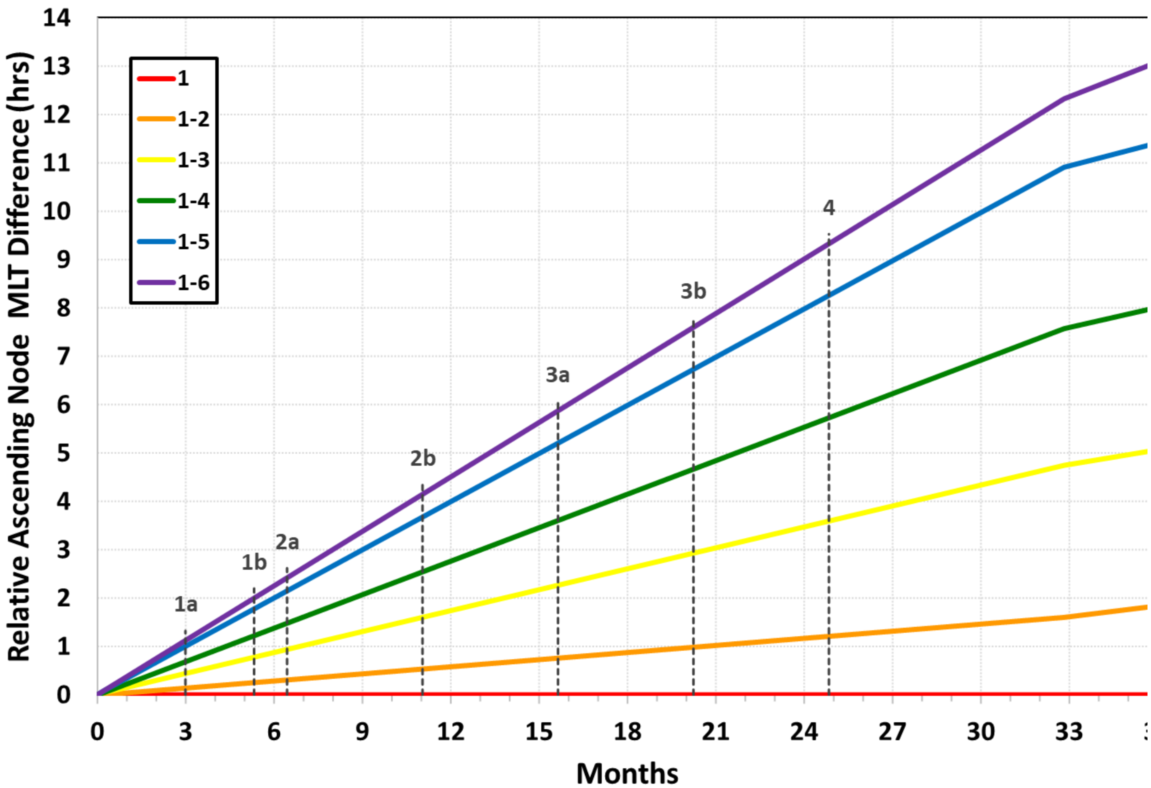

Figure 5 -- The separation of the six GDC orbit planes in Mean Local Time of the Ascending Node (MLT) relative to the orbit plane containing observatory G1, for the 36-month prime mission (including 90-day LEOC).

The slightly different inclinations cause the orbit planes to precess differentially, spreading apart in MLT (mean local time of ascending node). This behavior will continue beyond the end of Phase 4 (see below). **Figure 5** shows a summary of the difference in LTAN of the orbit planes, referenced to the plane containing G1, which has the slowest precession rate. Note that in addition to having a differential precession, the MLT of the whole constellation has a secular precession, taking the constellation through the full range of local times (ascending and descending nodes swap places) approximately every ~78 days. **Figure 6** shows the LTAN for each of the six observatories' orbit planes over time throughout the mission. For the purposes of the DRM, an initial LTAN (local time of the ascending node) of 1800 hours was chosen. The actual initial LTAN (and range of launch dates) will depend on requirements levied by the investigations and the mission design, and it will be refined throughout the formulation phase. **Figure 7** shows the relative "in-track" spacing of the six observatories in orbit phase (time difference between when observatories cross a given latitude on the ascending leg) as a function of mission phase. For the rest of this document, we will use the phrase "in-track" spacing to indicate the parameter described in the GDC STDT report as "synchronicity" – the difference between the time when a given observatory crosses a given latitude on the ascending leg of its orbit relative to the time at which a "reference" observatory crosses the same latitude on its ascending leg. It is important to remember that the six observatories are in six different orbital planes, so "in-track spacing" is not truly appropriate, but it is used here for convenience. Currently, the DRM calls for each spacecraft to maintain its "in-track spacing" relative to G1 within a window of **+/- 20 seconds.**

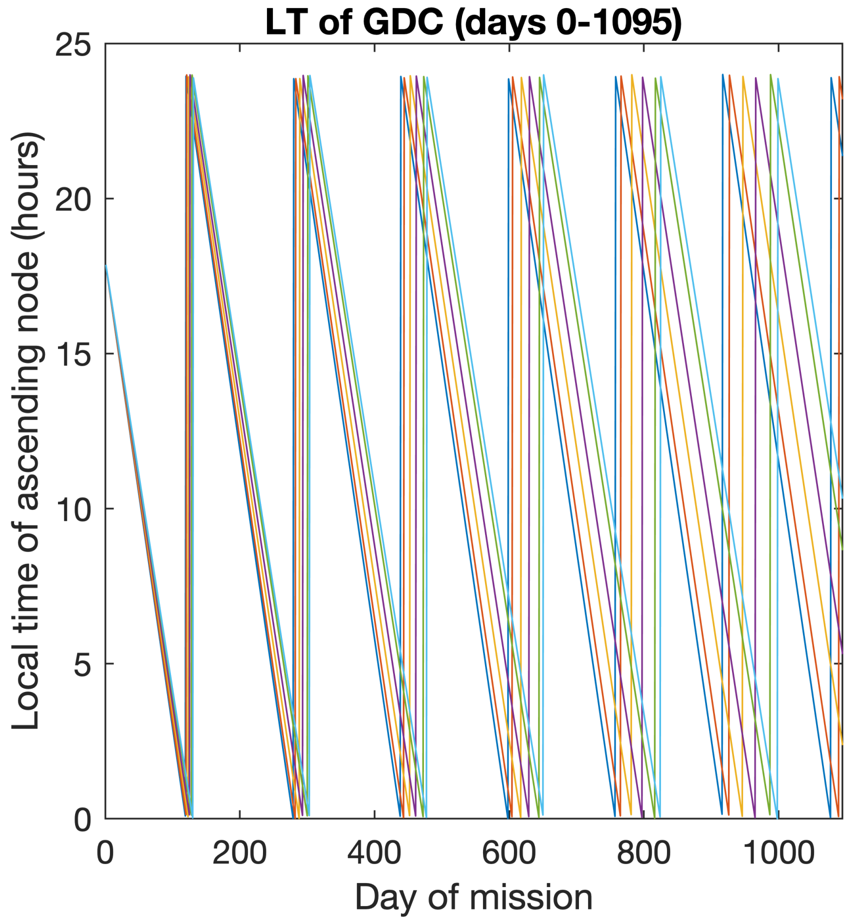

Figure 7 -- **tory G1 by**

Figure 6 -- The local time of the ascending node (LTAN) of the six GDC orbit planes, for the 36-month prime mission (including 90-day LEOC phase).

2.3 Inclination and Altitude variations

The DRM is designed to use "frozen orbits" to further minimize altitude variations at a given latitude. Frozen orbits exist when we exploit the Earth's orbital perturbations to keep the line of apsides (the line between perigee and apogee) fixed, aligned with the Earth's North and South Poles (*i.e.,* the apsidal precession rate is zero). In this orientation, the observatories will be at essentially the same geodetic altitude every time they fly over the same latitude. **Figure 8** shows the Geodetic Latitude versus the Geodetic Altitude orbit near the top (red), middle (green), and bottom (blue) of GDC's 350 – 400 km altitude corridor. *In the DRM, all six observatories are placed in nearly identical frozen orbits, so that they remain very tightly clustered together (within a few km) in altitude at any given latitude.*

For the purposes of efficient simulation of these ephemerides, it was decided to simulate the orbits without drag and to put the orbit in the middle of the altitude corridor (i.e. the green curve in **Figure 8**). Therefore, there are no drag make-up maneuvers in the simulated ephemerides to raise the orbits from the bottom to the top of the altitude corridor. Additionally, the "in-track" spacing remains constant for these orbits. In reality there will be small maneuvers to maintain the spacing

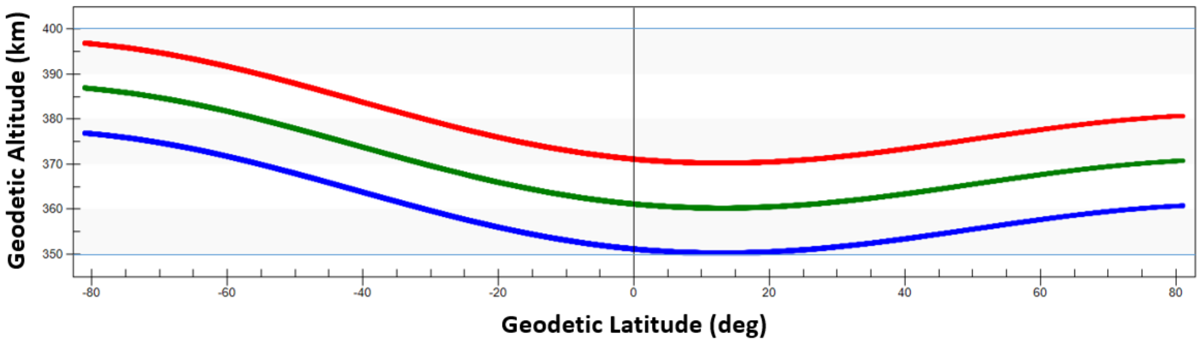

Figure 8 -- The geodetic altitude vs geodetic latitude for the "frozen orbits" of the GDC constellation. Each observatory will start with the red curve, at the top of the altitude corridor, and over the span of a few months will lose energy due to orbital drag, reaching the altitude/latitude profile shown by the blue curve. When this occurs, the observatory will be boosted in altitude back to the altitudes shown in the red curve.

caused by differential drag as the observatories encounter different drag environments and/or deplete propellant at different rates, but that was not modeled here. For planning purposes, one should assume that the altitude vs latitude curve for all six observatories will move through the family of curves in **Figure 8** every few months before the constellation is re-boosted to the top of the altitude corridor.

2.4 Spatiotemporal coverage of the DRM

Figure 9 shows the resulting spatiotemporal coverage of TVBs in the current version of the DRM. These are all valid TVBs with Q>=1.55 for the individual ITBs, and at least 25% areal overlap between the ITBs in the TVB. The spatial scale size is calculated as the square root of the TVB (overlap) area. The temporal scale is the time interval that gives maximal overlap of the ITBs in the TVB. The color scale denotes the log of the number of hours in which GDC has at least one TVB sampling in a latitude / local time / season / scale bin of the given spatial size and temporal scale. The large number of TVBs at one minute at all scales is an artifact of the way these are counted – the TVB is identified as the configuration at the time separation that results in maximal area overlap between component ITBs, and for this purpose only time separations of one minute or longer were examined. Because "self-TVBs" decrease in areal overlap monotonically, they will always have maximal overlap at the earliest time examined, in this case one minute. So by satisfying the criteria that led to the design of this DRM, GDC will automatically have coverage at local and regional scales at time separations faster than one minute. Note this coverage does not include virtual TVBs which may be formed by overlapping Virtual Sampling Baselines (VSBs).

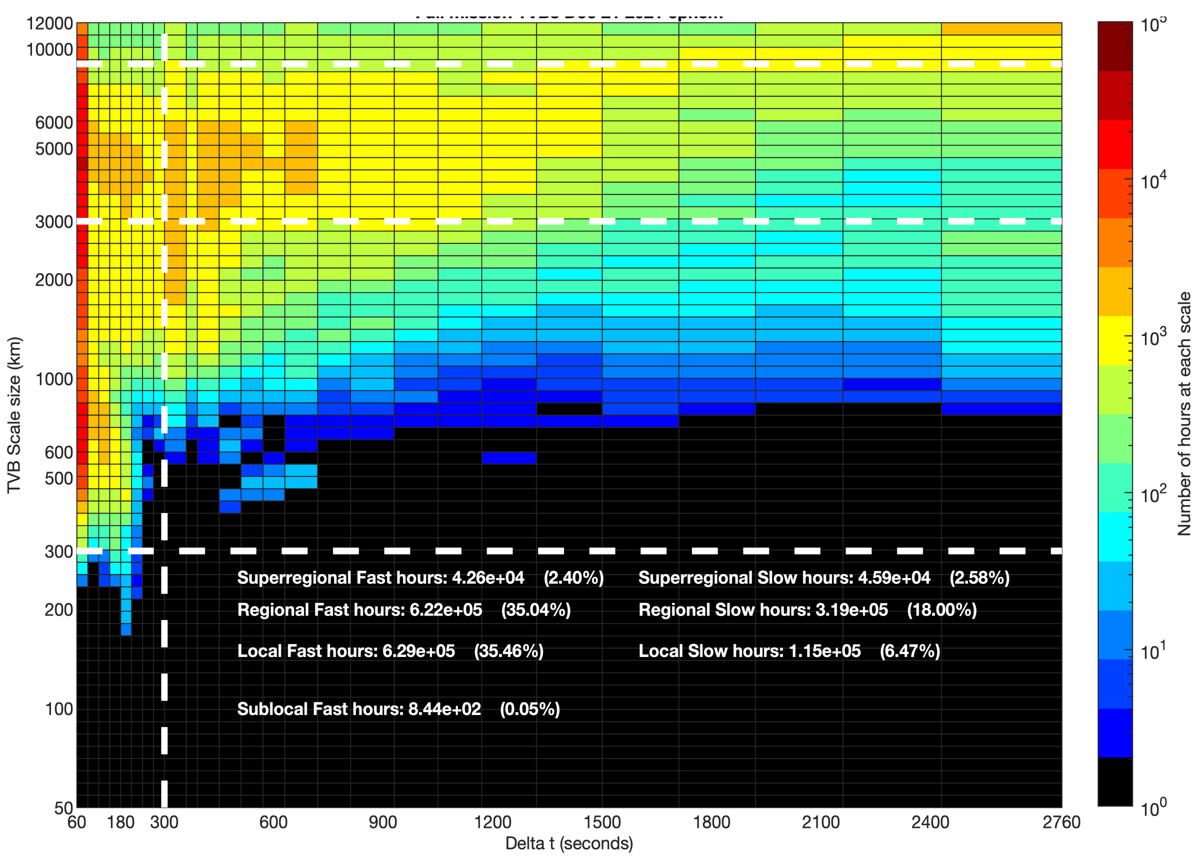

Figure 9—The spatiotemporal coverage of TVBs in the current DRM. The white dashed lines denote the boundaries of the LF, LS, RF, and RS scales.

2.5 Overview of the DRM mission phases

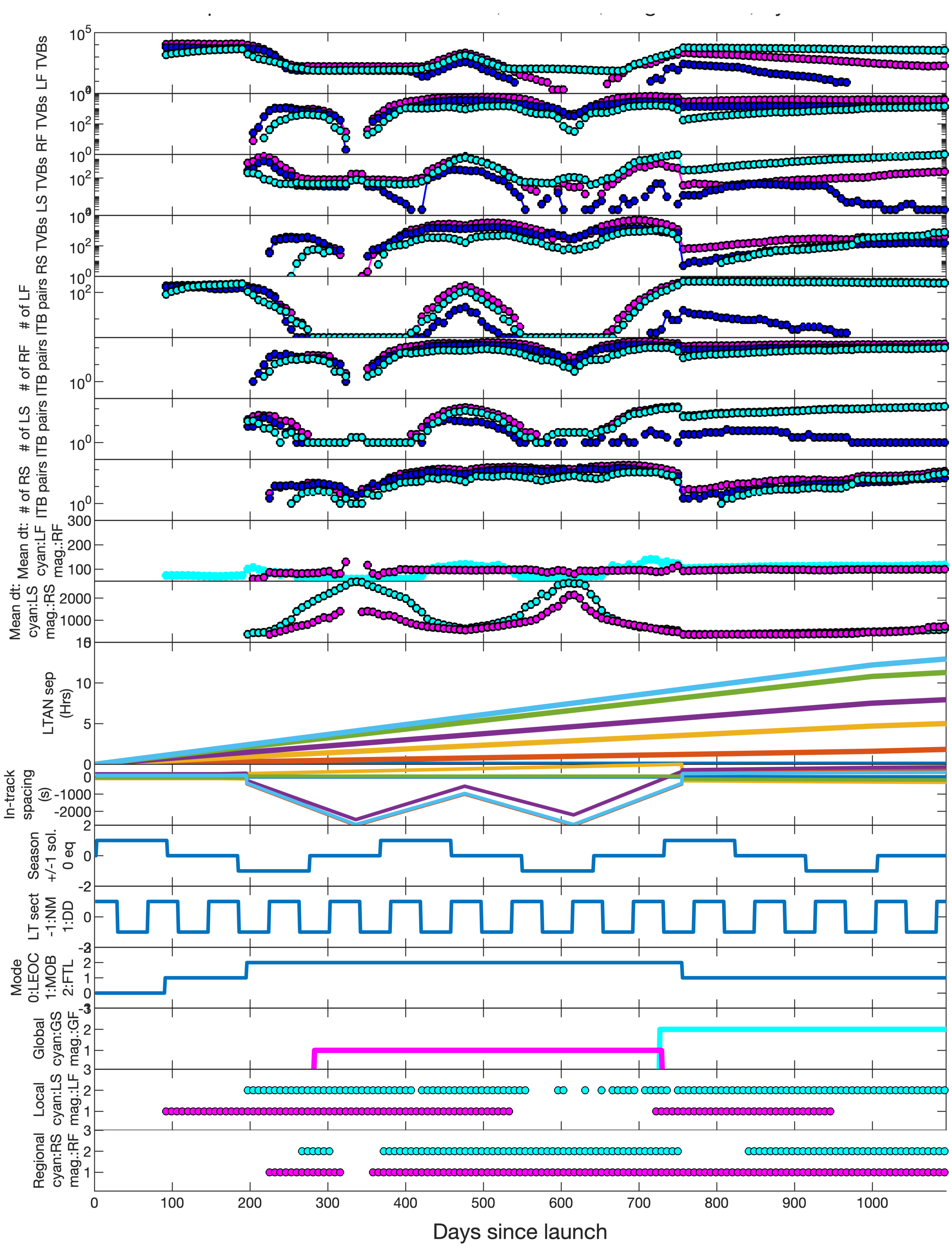

Figure 10—Overview of the scale, season, and local time coverage of the DRM

Figure 10 shows a summary-format overview of the DRM. The horizontal axis shows days since launch, spanning the full 36 month prime mission, including the 90-day Launch and Early Orbit / Commissioning (LEOC) phase at the beginning. The top four panels show the number of TVBs on each day of the mission, at one-week resolution, counted according to the criteria given previously, for each of the four scales LF, RF, LS, and RS, respectively. In each panel, there are three traces: dark blue for TVBs that occur at low latitudes, magneta for mid-latitude TVBs, and cyan for high-latitude TVBs. Due to the evolving geometry of the interspacecraft separations as the spacecraft move through their orbits, it is possible to have good Q values at some latitudes and not others. In this version of the DRM, things are biased towards high latitude coverage, because of the importance of GDC's Goal 1, and thus the low and mid latitudes are the first to drop out (see, for example the period in LF TVBs', panel 1, near days 550 to 700).

The next four panels show how many unique ITB-ITB pairs are producing valid TVBs at a given scale and a given latitude band on each day. There are at most twenty valid ITBs with six observatories, and so at most 200 unique ITB-ITB pairs (where order does not matter) that can be used to generate TVBs. The closer these values are to 200, the more "efficient" the constellation is at sampling at that scale. Note that during the Follow the Leader (FTL) periods (Phase 2 and 3) quite often the number of ITB pairs drops to 1 to 3, depending on the time separation between the FTL pairs, because the two ITBs are far enough apart in orbital phase that most of the potential ITBs have poor *Q* values.

The ninth and tenth panel show the mean TVB timescale for all valid TVBs for local (cyan) and regional (magenta) scales, with panel nine focusing on "fast" scale TVBs and panel ten focusing on "slow" scale TVBs. This clearly shows the "scanning" of TVB timescales during the FTL phases 2 and 3.

Panels eleven and twelve show the LTAN separation relative to observatory G1 and the in-track spacing relative to G1, which were previously shown in **Figures 5 and 7**, respectively. Panel thirteen shows the time history of the season in which GDC is making measurements, with +1 representing northern summer/southern winter, 0 representing either equinox, and -1 representing southern summer/northern winter.

Panel fourteen shows the mean local time of the GDC observatories, with -1 representing noon-midnight orbits, and +1 representing dawn-dusk orbits. Panel fifteen shows the "mode" of GDC's constellation vs. time, with 0 representing LEOC phase, 1 representing Multiple Overlapping Baselines (MOB) phase, and 2 representing FTL phase.

Panels sixteen through eighteen represent status flags to indicate whether GDC is measuring at a given scale on a given day. The presence of a non-zero value for panel sixteen shows that GDC is measuring Global-Fast scales (cyan) or Global-Slow scales (magenta). For panels seventeen and eighteen, non-zero values indicate slow (cyan) or fast (magenta) coverage for local scales (panel seventeen) or regional scales (panel eighteen). For these last panels, a non-zero value is only displayed if all three latitude bands (equatorial, mid-latitude, and high latitude) in panels one through four for the appropriate scale are nonzero.

Figure 11 -- The constellation configuration at the beginning of Phase 0 (LEOC). The lines indicate orbit planes – red, orange, yellow, green, blue, violet for G1 through G6 respectively. The left view shows the view looking down onto the northern hemisphere terminator (fixed local time). The right view shows the view looking at the equator directly onto the orbit plane containing the G1 observatory. During Phase 0 the orbit planes start at the same LTAN (with slightly different inclinations). An initial launch LTAN of 1800 hours was chosen for the purposes of the DRM.

2.6 Detailed description of the DRM Phases

2.1.9. Phase 0: Launch and Early Operations / Commissioning (LEOC) **Days 1-90**

During LEOC, the observatories are being commissioned, and they are not officially yet in "science mode", which means that one should not plan to use data during this period (though initial calibration data will be taken during this phase, when the observatories are close together, providing inter-observatory calibration data). The constellation configuration during LEOC is:

1) The orbit planes are close together as they precess through nearly all local times. **Figure 11** shows the orbital plane configuration just after launch. At the start of LEOC, all six planes have slightly different inclinations, but the same local time of the ascending node (LTAN).

2) The spacing of the observatories within the orbit is TBD, consistent with safety and practical considerations while the spacecraft and instrument systems are being checked out. This period permits some opportunities for inter-calibration of the instruments on different observatories, as they will experience similar environments, in general. For now, it is reasonable to assume that they will remain at least 40 seconds apart in in-track spacing, though at times they may be up to ~15 minutes apart (evenly spaced along the orbit)

3) The observatories are maintained in "frozen orbits" (see **Section 2.4**) so that each encounters a given latitude within a narrow range of altitudes. The altitudes of the constellation will evolve under orbital drag, slowly lowering over time. *Note: as described above, drag is not explicitly accounted for in the simulated ephemeris, but*

given current expectations for solar activity, "drag makeup maneuvers", which will boost the constellation and keep perigee above 350 km, are expected every few months.

At the end of the 90-day LEOC phase, maneuvers adjust the constellation to prepare for the beginning of the science phases of the GDC mission, beginning with Phase 1a.

2.1.10. Phase 1: Local-Fast / Multiple Overlapping Baselines (MOB) **Day 91-195**

Phase 1 marks the beginning of full science operations for the GDC constellation.

During this phase, the six GDC observatories have orbit planes that are relatively close together. The in-track spacing of the observatories is optimized for sampling of relatively small or "local" scale features, with horizontal gradient scale sizes ranging from a few hundred to a few thousand km (see **Figure 12**). In Phase 1, the observatories are in a "Multiple Overlapping Baselines" (MOB) configuration, with all six spacecraft within +/- 3 minutes of G1. This configuration provides up to twenty ITBs with high *Q* values, with overlapping footprints, to allow the best constraints for estimating spatial gradients of small-scale features and their time rates of change. This close spacing also permits assessment of temporal changes that occur faster than ~5 minutes ("local-fast" observations).

During all of Phase 1, the differential precession of the orbit planes continues, causing them to continue to spread in LTAN, and the overall secular local time drift of the constellation continues, sweeping out the full range of local times every ~78 days.

Phase 1 is divided into two subphases, to maintain good sampling geometry, as quantified by the *Q* value for the ITBs:

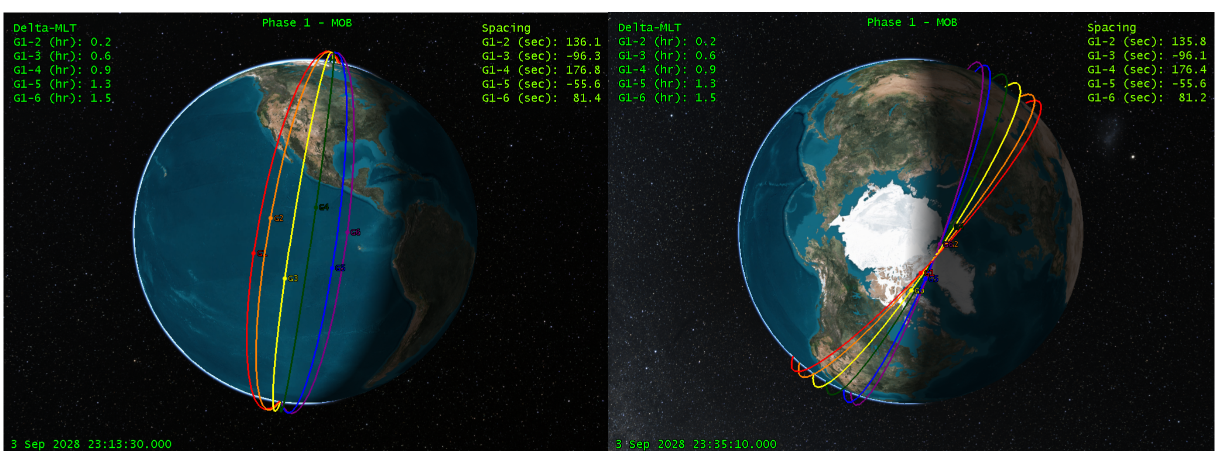

Figure 12 – Representative examples of the relative positioning of the six observatories during Phase 1 near the equator (left) and pole (right). This configuration is referred to as a "MOB" (multiple overlapping baselines), and it provides well-constrained measurements of spatial variation, as well as measurements of rapid temporal variation.

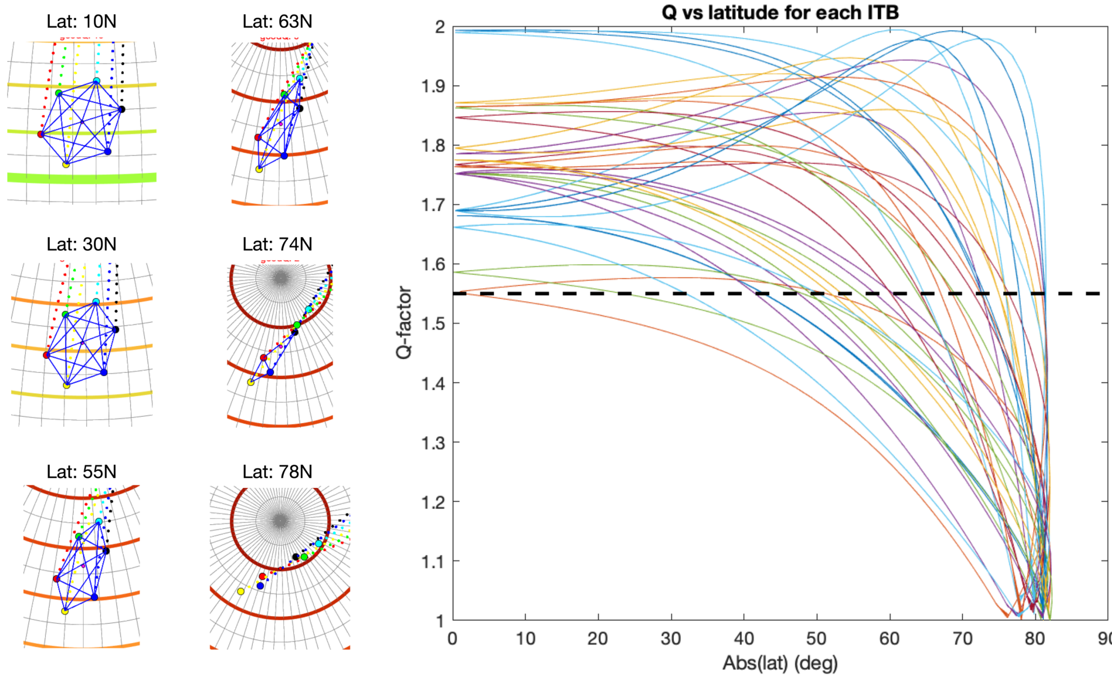

Figure 13 – (left, middle) – For day 092, the relative spacing of the six observatories as they progress in latitude from just beyond the ascending node (10 degrees N latitude, top left) through nearly their maximum latitude. Individual ITBs are shown when they have *Q* values>=1.55. (right) The *Q* values of all 20 ITBs on a single orbit vs absolute value of latitude on day 092.

- Day 91-162: **Phase 1a** -- "Local-Fast, nonscaling" phase, which strongly constrains local-scale spatial structures while permitting studies of time variations of these structures on timescales of 30 seconds up to a few minutes. In this phase, the spacecraft have the minimum synchronicity set by safety considerations of +/- 20 second tolerance "control boxes" – that is, the closest two spacecraft are nominally ~40 seconds apart in in-track spacing. The spacings of the observatories relative to G1 are: [0, +136, 96, +177, -55, +82] seconds.

- Day 163-195: **Phase 1b** – "Local-Fast, scaling" phase, which is the same as 1a, except that by the start of Phase 1b, the orbit plane LTANs have spread apart enough to permit better *Q* values for the sampling ITBs. To ensure this, the spacecraft "in-track" spacings are not fixed but are allowed to slowly drift in a linear fashion, so as to match the LTAN spreading due to the different orbit inclinations. The exact spreading rate was determined by maximizing *Q* near 55 degrees geographic latitude, and assuming all spacecraft satisfied their +/- 20 second "control box" relative to G1. To achieve this, the observatories are given very small differences in semimajor axis (total of 170 meters spread across the six observatories). At the beginning of this phase the spacings relative to G1 are [0, +136, -96, +177, -55, +82] seconds, and at the end, [0, +162.7, -114.8, +211.7, -65.8, +97.7].

Figure 13 shows the GDC MOB configuration at various latitudes near the beginning of Phase 1a (day of mission 092).

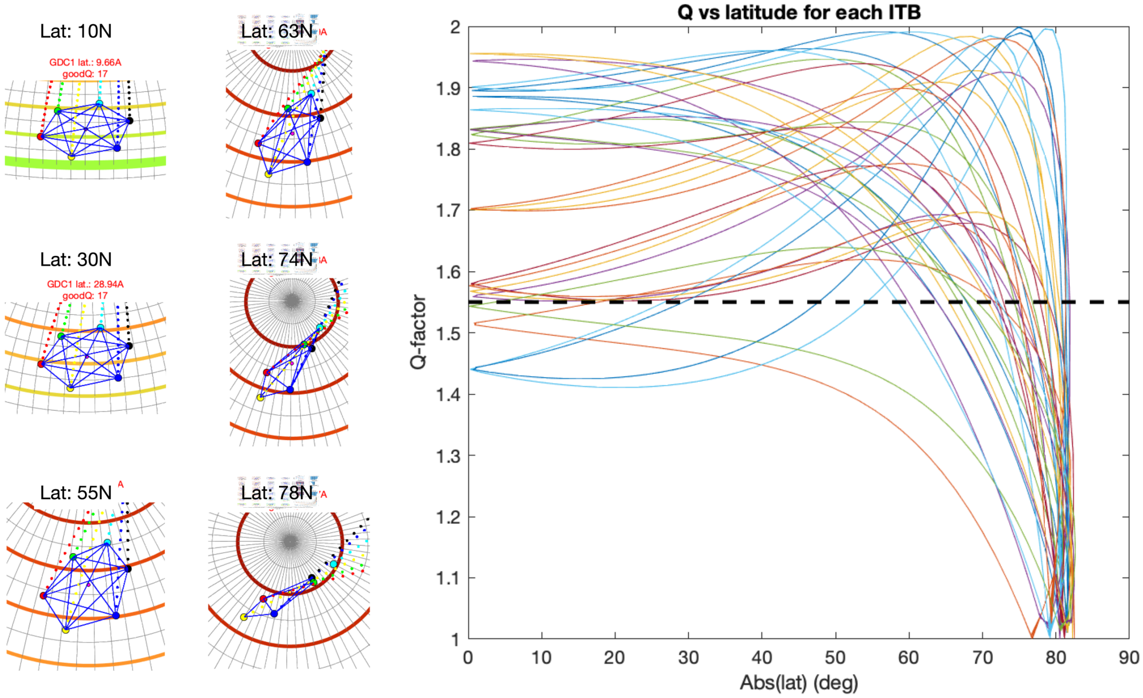

Figure 14 – (left, middle) – For day 169, the relative spacing of the six observatories as they progress in latitude from just beyond the ascending node (10 degrees N latitude, top left) through nearly their maximum latitude. Individual ITBs are shown when they have *Q* values>=1.55. (right) The *Q* values of all 20 ITBs on a single orbit vs absolute value of latitude on day 169.

Figure 14 shows the GDC configuration near the beginning of Phase 1b. The orbit plane LTANs have spread sufficiently by this point to permit the in-track spacing to scale linearly, providing a “self-similar” geometry throughout the rest of Phase 1b. Note that the *Q* values of the ITBs are generally optimized to be maximal near 50-65 degrees latitude, sacrificing some isotropy near the equator. This provides better sampling at the highest latitudes encountered by GDC as well.

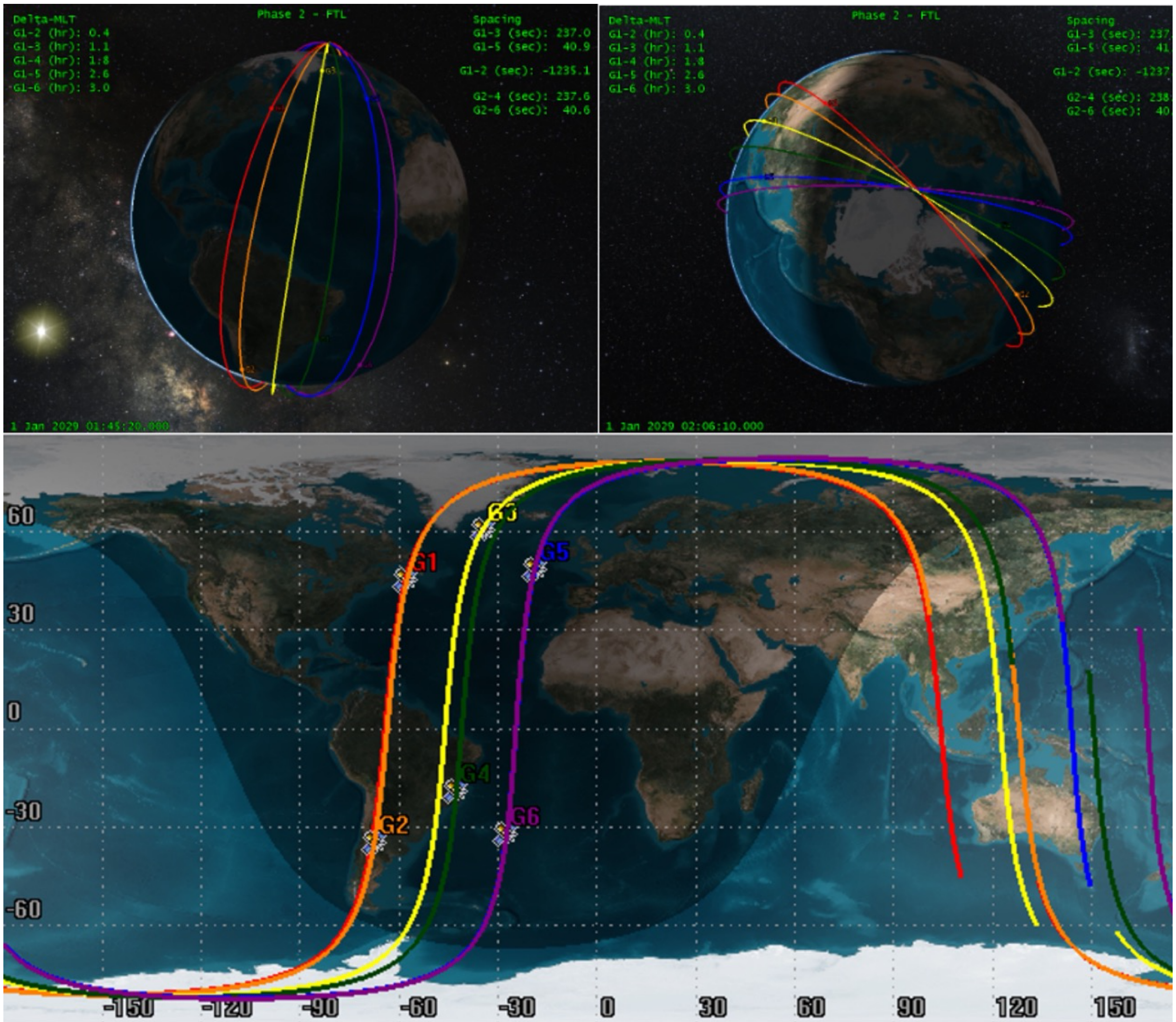

Figure 15-- Representative examples of the relative positioning of the six observatories during Phase 2 near the equator (top, left) and pole (top, right). (bottom) Mercator projection showing the geometry, with G1, G3, G5 leading G2, G4, G6. This configuration is referred to as a "FTL" (follow the leader), and it provides well-constrained measurements of spatial variation, for slower temporal variations.

2.1.11. Phase 2: Local Slow / Follow the Leader (FTL) **Day 196-476**

Phase 2 provides the predominant observations at local-slow scale, using a "Follow The Leader" scheme, where the six observatories are divided into two "teams" of three: the "red team" G1, G3, and G5, and the "green team" G2, G4, G6. The red team leads the green team, with each team providing a single ITB measurement baseline, but with a variable time difference between when the ITBs observe at a given location. **Figure 15** shows the orbit plane spacing and representative positions for the observatories in Phase 2. During this phase, the focus is on measuring spatial gradients but also permitting assessment of slower rates of change, ranging from a few minutes up to half an orbit period and beyond.

The two teams are in orbits with slightly different semi-major axes (SMAs) – with the red team about 1.8 km lower than the green team. Over time, this difference in SMA and the corresponding

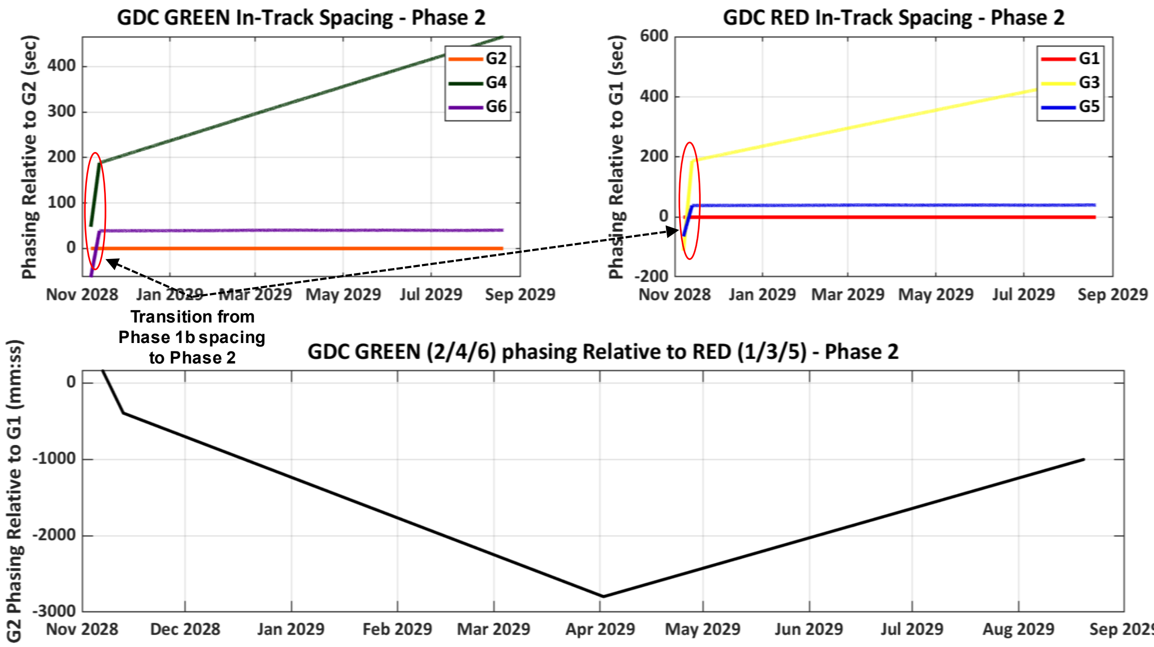

Figure 16 -- The "in-track" separation between observatories in Phase 2. G1, G5, G5 form the "green team", with a given (scaling with time, analogous to Phase 1b) orbit phase separations between them, and G2, G4, and G6 form the "red team" with a different set of orbit phase separations. The bottom panel shows the relative separation between red (leading) and green (lagging), and it shows that this grows to ~½ an orbit period and then back to ~1000 seconds. Also shown is a ~six-day transition period where the constellation is rearranged from the configuration at the end of Phase 1b.

difference in orbit period causes the red team to advance ahead (in orbit phase) of the green team in orbit phase. **Figure 16** shows how, with time, the red team will scan through the full range of phase delays / time separations relative to the green team, allowing GDC to examine local-scale temporal variations between 5 minutes and ½ and orbit period.

At this rate of drift, the red team is ½ orbit ahead of green after 140 days. This first subphase is "Phase 2a". At this time, the red team's SMA is increased to be 1.8 km over the green team, and the relative in-track drift reverses until after another 140 days the two teams cross the same latitude with about 1000 seconds of delay. This second half of Phase 2 is "Phase 2b"

During the whole of Phase 2, the individual "team" ITBs are also slowly scaling in relative in-track spacing to maintain their individual high-*Q* geometry, as can be seen in the top two panels of **Figure 16**.

This scheme is chosen because the red team is on average at slightly earlier local times relative to the green team, and thus having the red team "lead" partially counteracts the effects of Earth rotation and allows GDC to sample parcels of atmosphere more consistently.

2.1.12. Phase 3: Regional Slow / Global Fast (FTL) **Day 477-756**

Phase 3 provides the predominant observations at regional-slow scale, analogous to Phase 2, but with a greater spread in LTANs between the orbit planes and commensurately greater in-track

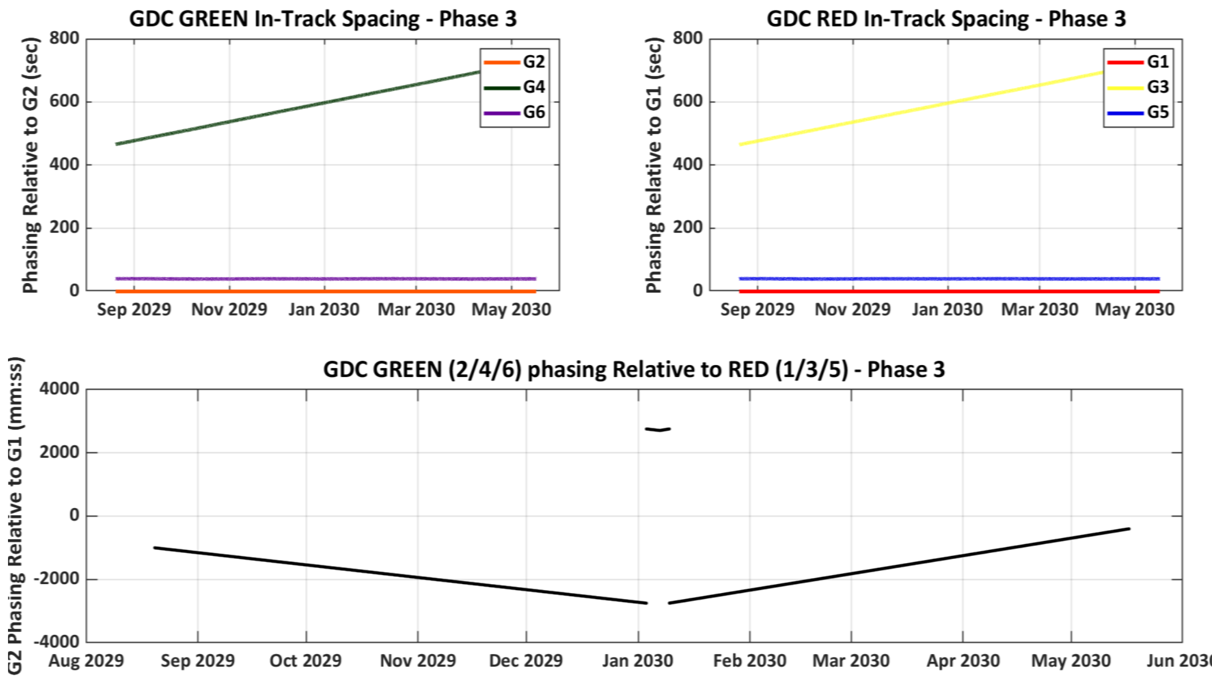

Figure 17 -- The "in-track" separation between observatories in Phase 3.

spacings to maintain good Q values for the ITBs. **Figure 17** shows the orbit plane spacing in Phase 3. During this phase, the focus is on measuring spatial gradients but also permitting assessment of slower rates of change, ranging from a few minutes up to half an orbit period and beyond. Towards the end of Phase 3, the orbit planes have spread far enough in LTAN that the two FTL "teams" provide global-scale measurements at "fast" (15-45 minute) timescales.

The two teams are in orbits with slightly different semi-major axes (SMAs) – with the red team about 1.8 km lower than the green team. Over time, this difference in SMA and the corresponding difference in orbit period causes the red team to advance ahead (in orbit phase) of the green team in orbit phase. **Figure 17** shows how, with time, the red team will scan through the full range of phase delays / time separations relative to the green team, allowing GDC to examine local-scale temporal variations between 5 minutes and ½ and orbit period.

At this rate of drift, the red team is ½ orbit ahead of green after 140 days. This first subphase is "Phase 3a". At this time, the red team's SMA is increased to be 1.8 km over the green team, and the relative in-track drift reverses until after another 140 days the two teams cross the same latitude with about 1000 seconds delay. This second half of Phase 3 is "Phase 3b"

During the whole of Phase 3, the individual "team" ITBs are also slowly scaling in relative in-track spacing to maintain their individual high-Q geometry, as can be seen in the top two panels of **Figure 17**.

2.1.13. Phase 4: Regional Fast / Global Slow (MOB) **Day 757-1095**

Phase 4 provides the predominant observations at regional-fast and global-slow scales, by using a MOB scheme, where the six observatories are grouped close together to provide better local time resolution in the global mode, and to provide better constraints on spatial variations in regional-fast configurations (particularly early in phase 4 and at high latitudes). **Figures 18 and 19** show representative configurations during this phase. Note that shortly after day 900, the orbit planes for G1 and G6 have LTANs that are separated by twelve hours.

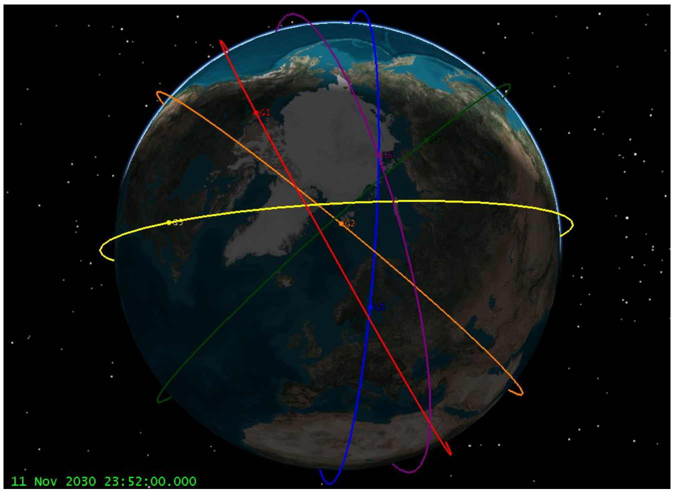

Figure 18 -- The LTAN separation in Phase 4

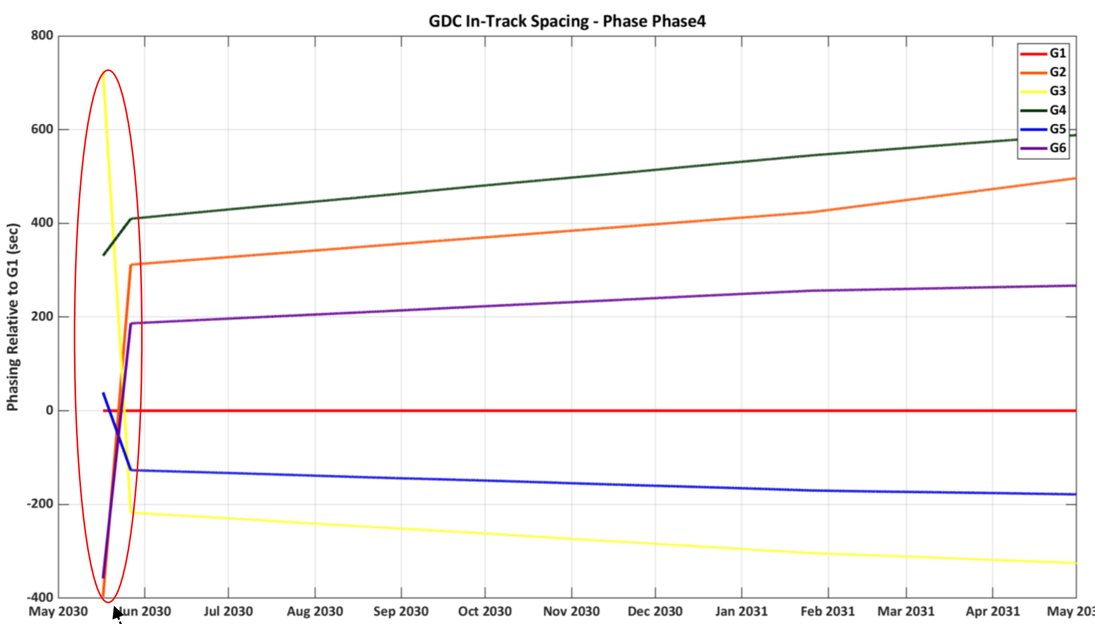

Figure 19 -- The "in-track" separation between observatories in Phase 4. The observatories are in a "scaling MOB" formation analogous to Phase 1b. There is a ~10-day transition period to get to this configuration after the end of Phase 3b.

2.7 Ephemeris file format

Ephemeris files were generated for each of the GDC observatories for each Mission Phase. These plain, ASCII text files contain the following orbital information.

- Time is given in Mission Elapsed Days with hour:minute:second time steps. The time interval is 30 seconds. Example: 91/00:00:00.000 [Day 91, Time 00:00:00.000 UTC]
- XYZ Cartesian Position is given in Earth J2000 inertial coordinates [X-J2K, Y-J2K, Z-J2K]
- XYZ Cartesian Velocity is given in Earth J2000 inertial coordinates [Vx-J2K, Vy-J2K, Vz-J2K]
- Geodetic Latitude, Longitude, and Altitude [LAT, LON, ALT] are computed using the WGS84 parameters for Earth's mean equatorial radius and flattening coefficient
- XYZ Solar Position unit vector is given in Earth J2000 inertial coordinates [Xsun-J2K, Ysun-J2K, Zsun-J2K]
- The vector from Earth center to the intersection of Earth's Equator and Prime Meridian is given in Earth J2000 inertial coordinates [Xpm-J2K, Ypm-J2K, Zpm-J2K]

The ephemeris data files generated for the DRM can be found at the following URL:
https://ccmc.gsfc.nasa.gov/missionsupport/GDC_support.php

Specifically, Rev C of the DRM corresponds to the ephemeris files at:
https://ccmc.gsfc.nasa.gov/RoR_WWW/GDC_support/Proposer_Resources/GDC_EphemerisRevC.zip

There is a movie in the .zip archive that contains the ephemeris files (**GDC_DRM5.mp4**) that shows how the orbit planes spread out over time. The movie shows the motion of orbit planes in two separate frames and views. The view on the left is displayed in the Geocentric Solar Ecliptic coordinate frame. In this view, we are looking down on the Ecliptic Plane with the Sun always to the left. We can see that the orbits will precess through all local times (and Beta angles). The view on the right is displayed in a Geocentric Equatorial Inertial frame. In this view, we are fixing the viewpoint with the plane of G1's orbit. As the movie progresses, we see how the other orbit planes move relative to G1's orbit plane. In both movies, the angles between the G1 orbit plane and the other orbit planes are overlaid in green text in the top left.

The .zip archive contains a second movie (**GDC_DRM_Phase2_FTL_1.mp4**) that shows the motion of the observatories during the Phase 2 Follow The Leader (FTL) scenario. The movie shows the six GDC orbit planes, with triangles highlighting the two separate teams: Red (G1/G3/G5) and Green (G2/G4/G6).

A sample of an ephemeris file, showing the data format, is given on the next page.

Sample Ephemeris Data

GDC_Ephemeris_UTC_G1_ND_Phase1.txt

28 Feb 2022 16:59:26

Satellite-G1_ND

Time (UTCG)	X-J2K (km)	Y-J2K (km)	Z-J2K (km)	Vx-J2K (km/sec)	Vy-J2K (km/sec)	Vz-J2K (km/sec)	LAT (deg)	LON (deg)	ALT (km)	Xsun-J2K	Ysun-J2K	Zsun-J2K	Xpm-Y2K	Ypm-J2K	Zpm-J2K
31 Jul 2028 00:00:00.000	997.865	-477.296	6636.332	1.604248	7.519662	0.298967	80.740	25.237	370.575	-0.614595	0.723789	0.313692	0.626254	-0.779617	-0.001754
31 Jul 2028 00:00:30.000	1045.399	-251.471	6641.401	1.564350	7.533887	0.038963	81.016	37.336	370.598	-0.614600	0.723785	0.313690	0.627958	-0.778245	-0.001759
31 Jul 2028 00:01:00.000	1091.708	-25.351	6638.669	1.522620	7.539287	-0.221086	80.877	49.619	370.588	-0.614606	0.723781	0.313688	0.629659	-0.776869	-0.001764
31 Jul 2028 00:01:30.000	1136.738	200.798	6628.139	1.479106	7.535857	-0.480876	80.340	61.028	370.547	-0.614612	0.723777	0.313686	0.631357	-0.775490	-0.001768
31 Jul 2028 00:02:00.000	1180.437	426.712	6609.822	1.433858	7.523601	-0.740104	79.465	70.889	370.474	-0.614617	0.723773	0.313684	0.633052	-0.774107	-0.001773
31 Jul 2028 00:02:30.000	1222.753	652.126	6583.741	1.386931	7.502532	-0.998468	78.328	79.034	370.370	-0.614623	0.723769	0.313682	0.634744	-0.772720	-0.001778

Appendix A Abbreviations and Acronyms

ALT	Altitude
AO	Announcement of Opportunity
DRM	Design Reference Mission
FTL	Follow the Leader
GDC	Geospace Dynamics Constellation
GF	Global-Fast scale
GS	Global-Slow scale
GSFC	Goddard Space Flight Center
G1, G2, …G6	Individual observatory numbers
IT	Ionosphere-Thermosphere
ITB	Instantaneous Triangular Baseline
LF	Local-Fast scale
LAT	Latitude
LON	Longitude
LS	Local-Slow scale
LSGC-AS	Least Squares Gradient Calculation with Adaptive Scaling
LTAN	Local Time of the Ascending Node
LWS	Living With a Star
MLT	(in this context) Mean Local Time of the Ascending Node
MOB	Multiple Overlapping Baselines
NASA HQ	NASA Headquarters
RF	Regional-Fast scale
ROI	Region of Interest
RS	Regional-Slow scale
SCHA	Spherical Cap Harmonic Analysis
SECS	Spherical Elementary Current System analysis
STDT	Science and Technology Definition Team
TAD	Traveling Atmospheric Disturbance
TID	Traveling Ionospheric Disturbance
TBD	To be determined
TBR	To be revised
TBS	To be scheduled
TMC	Technical/Management/Cost review
TVB	Temporal Variation assessment Baseline
VSB	Virtual Sampling Baseline

Appendix B References

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