GDC-AO-DRMPED

Revision B

Geospace Dynamics Constellation Design Reference Mission: Predicted Ephemeris Description

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Change History Log

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.

Table of Contents

List of Figures

List of Tables

1 INTRODUCTION

1.1 Purpose

This document presents the mission phases, constellation configuration, and predicted ephemerides for the Geospace Dynamics Constellations's (GDC) "Design Reference Mission" (DRM). GDC's DRM is the plan for configuring 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 developed as part of GDC pre-formulation activities and 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

Links to download this document and the described ephemeris files are provided on NASA's Science Office for Mission Assessment website for Geospace Dynamics Constellation, which can be found at: https://lws.larc.nasa.gov/GDC. This document and the ephemeris files can also be downloaded directly from https://ccmc.gsfc.nasa.gov/missionsupport/GDC_support.php.

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

1.3 Related Documentation

1.3.1 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 (to be released as part of the AO)

2 GENERAL

2.1 DRM Guiding Principles and Assumptions

The GDC DRM represents one potential approach to gather the observations required to meet GDC's Science Objectives. It was developed with the following top-level principles in mind:

1) The DRM was developed as a constellation consisting of **six identical observatories** in order to demonstrate a proof of concept architecture that could address the GDC Science Objectives.

2) The DRM was designed to provide sampling at all spatiotemporal scales outlined in the GDC 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 in order to more 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.

4) The DRM was designed to gather data over as much of the globe (geographic latitude and geomagnetic latitude) as practical in order 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 of 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 also serve as a guide to the general types of constellation sampling configurations that can readily be achieved.

8) The DRM was developed as a high-fidelity simulation that accounts for nearly all the significant orbital perturbations, but it did not include drag effects. GDC is planned 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 of the DRM. 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 2.4**.

2.2 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 (Objectives 1.1, 2.1, and 2.3)
2) Much more accurate assessment of spatially-integrated heating rates that drive changes in neutral density (Objective 1.3)
3) Much more accurate assessment / constraints on bulk motion / convection patterns that drive changes in plasma and neutral density (Objectives 1.2 and 1.3)

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.*

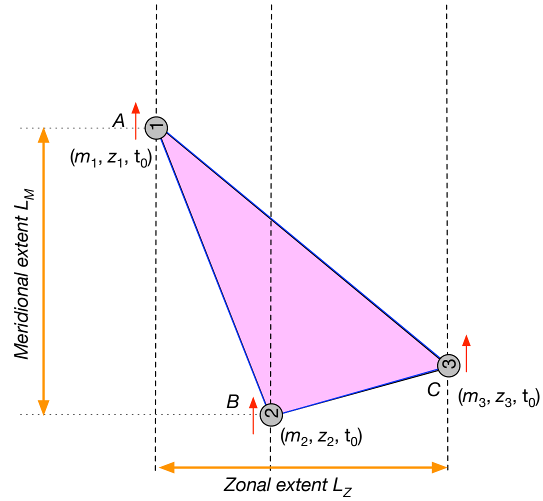

Figure 1-- Any three non-collinear observatories, forming an Instantaneous Triangular Baseline, or ITB, can be used to measure the instantaneous average value of a parameter and its meridional and zonal gradients within a triangular region *ABC*.

In order 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, 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 baseline of length L_Z and a meridional 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. 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, and thus, given the significant complexity of adding additional sampling points at dramatically different altitudes, addition of measurements at multiple altitudes was not deemed to be of significant

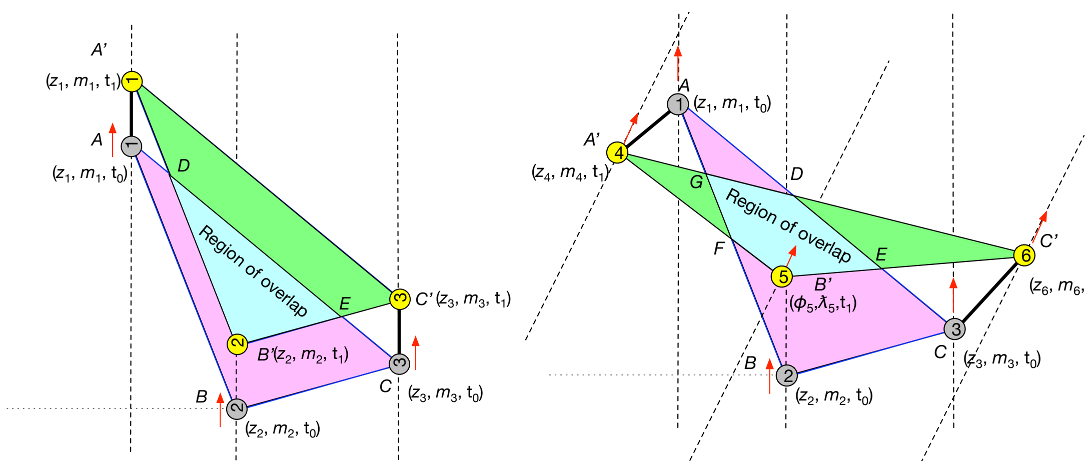

Figure 2-- Examples of TVBs: (left) Two subsequent, overlapping ITBs can be combined to form a Temporal Variation assessment Baseline (TVB), which can be used to measure the time variation in the average value of a parameter and its meridional and zonal gradient within a polygonal region *A'C'CBA*. Here,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

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 DRM.

Thus, the GDC sampling scheme focuses on measurements of horizontal gradients using groups of three observation points separated in latitude and longitude (i.e. not collinear), but closely spaced in altitude. This approach is most useful for **local-scale and regional-scale** phenomena, where a gradient can be meaningfully computed.

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*. 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. While less frequent, these second types of 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.

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 3.**

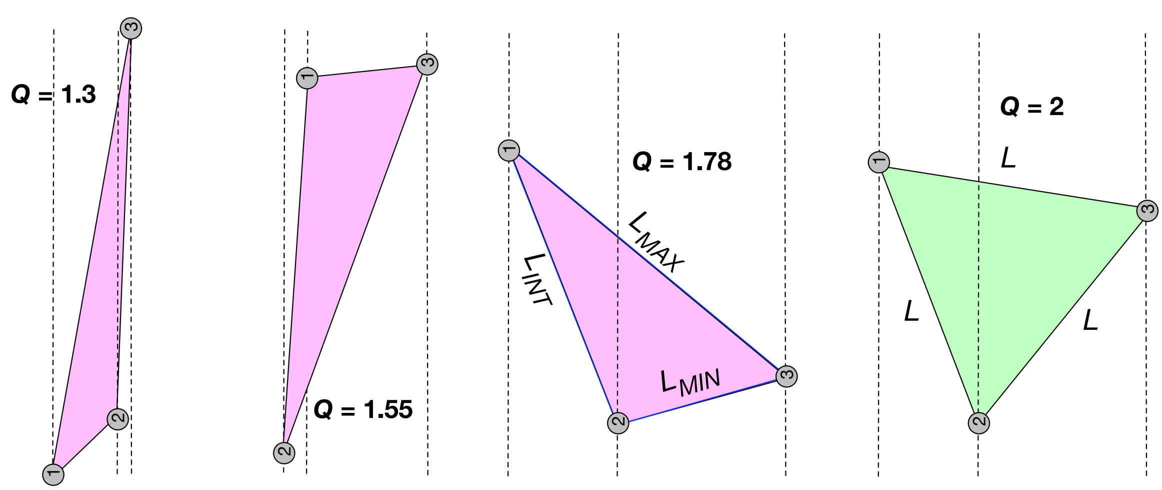

Figure 3-- Examples of ITBs with different values of *Q*. Larger values of *Q* provide better estimations of average parameters and their horizontal gradients, in the isotropic case.

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

$s = \frac{1}{2}[L_{MAX} + L_{MIN} + L_{INT}]$ — s is the "half perimeter" of the ITB.

$A_{actual} = \sqrt{s(s - L_{MAX})(s - L_{INT})(s - L_{MIN})}$ — actual area of the ITB

$A_{ideal} = \sqrt{3}\left(\frac{s}{3}\right)^2$ — area of an equilateral ITB of equal perimeter

$Q = 1 + \left(\frac{A_{actual}}{A_{ideal}}\right)$ — Q = 2 is ideal, Q = 1 indicates collinearity

Ideally, the 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 give reasonable values of Q, over the full range of local and regional scales.

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

Mnemonic	Scale name	Scale size description	Spatial Scale[1], L	Temporal Scale[2], τ
LF	LOCAL-FAST	Local Scale, for rapid variations	300-2000 km	0.5 – 3 minutes
LS	LOCAL-SLOW	Local Scale, for slower variations	300-2000 km	>3 minutes
RF	REGIONAL-FAST	Regional Scale, for rapid variations	2000-4000 km	0.5 – 6 minutes
RS	REGIONAL-SLOW	Regional Scale, for slower variations	2000-4000 km	>6 minutes

[1]Spatial scale, L, applies to both zonal (L_Z) and meridional (L_M) scale sizes. Both must fall into this range.

[3]Temporal scale, τ, describes the range of temporal separations over which measurements must be made in order 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.

Scale	Scale name	Scale size description	1st pair sep, LTAN[1]	2nd pair sep, LTAN[2]	Mean LTAN Sep.[3]	LTAN Span	Synch	Revisit Time
GS	GLOBAL-SLOW	Global Scale, for slower variations	2-4 hr	3-6 hr	<4 hr	>= 4.5 hr	<15 min.[4]	1 orbit period (~94 min)
GF	GLOBAL-FAST	Global Scale, for more rapid variations	3-6 hr	3-6 hr	<4 hr	>=3 hr	<15 min.[5]	15 min. to ½ orbit period (~47 min)

[1]At least one pair of spacecraft (pair **a**) must be separated in LTAN (local time ascending node) by this amount (inclinations presumed > 80° and within 1° of each other), and must make measurements at a given latitude within the "Synchronization" range in the seventh column

[2]At least one pair of spacecraft (pair **b**) must be separated in LTAN by this amount (inclinations presumed > 80° and within 1° of each other), and must make measurements at a given latitude within the "Synchronization" range in the eighth column

[3]The mean LTANs, calculated for each of the two pairs of spacecraft, must be within this range

[4]All spacecraft contributing to this scale must make measurements at any given latitude within this time range.

[5]All spacecraft in pairs **a** and **b,** separately, on a per-pair basis must make measurements at any given latitude within this time range. Each pair will have a mean measurement time at a given latitude, and the separation between these mean sampling times must fall in the range given in the eighth column.

Table 2-- Definitions of global scale sizes for GDC.

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 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.

2.3 General outline of the DRM

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 /

Phase	Start day	End day	LF	LS	RS	RF	GS	GF
1a	*91*	*190*						
1b	*191*	*290*						
2a	*291*	*390*						
2b	*391*	*425*						
3a	*426*	*763*						
3b	*764*	*842*						
3c	*843*	*1094*						

Table 3 – The phases of the GDC DRM. For each phase, this table shows the day (elapsed days since launch) 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)

	Initial insertion by LV	Following burn early in LEOC	Following burn at the end of Phase 3b
G1	81.0°	81.0°	81.5°
G2		81.23°	
G3	81.45°	81.33°	
G4		81.56°	
G5	82°	81.69°	
G6		82°	

Table 4 – Orbital inclinations of the six GDC observatories (G1, G2, ...G6) during the mission. The orbits will experience perturbations which drive small cyclical variations in the inclination over time, but these are the nominal values.

Commissioning (LEOC), and on day 1095 the constellation will either go into an extended mission or undergo a controlled 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 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.

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 until the end of Phase 3b (see below). **Figure 4** shows a summary of the difference in MLT of the orbit planes,

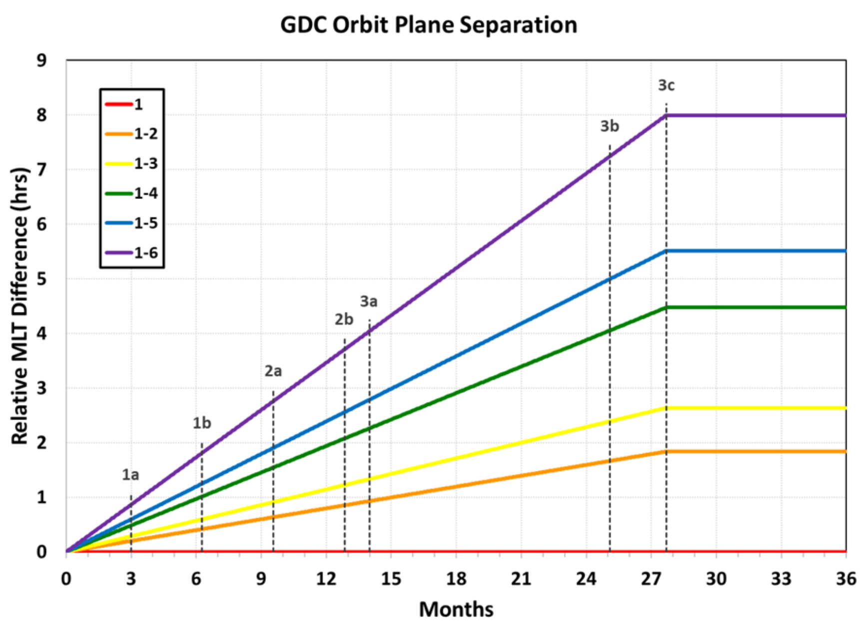

Figure 4 -- The separation of the six GDC orbit planes in Mean Local Time of the Ascending Node (MLT) relative to the orbit plane containing observatory G1, for the 36-month prime mission (including 90-day LEOC).

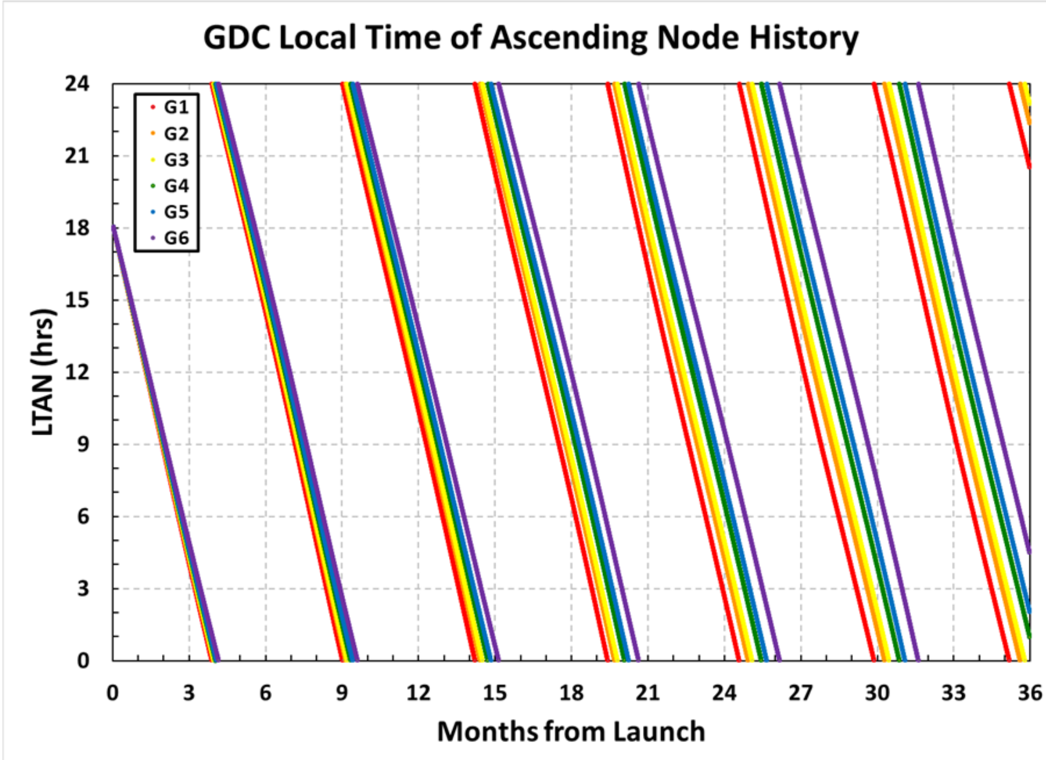

Figure 5 -- The local time of the ascending node (LTAN) of the six GDC orbit planes, for the 36-month prime mission (including 90-day LEOC phase).

referenced to the plane with 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 5** shows the MLT 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. **Table 5** 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.

2.4 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

	GDC Mission Phase in-track spacings (± 20 seconds for non-ref s/c)						
	1a	1b	2a	2b	3a	3b	3c
G1	-21	-42	-87	-141	-141	-192	-192
G2	0	0	0	0	0	0	0
G3	-103	-124	-229	-403	-523	-484	-484
G4	+21	0	0	+51	+51	0	0
G5	-144	-144	-264	-444	-594	-504	-504
G6	-62	-62	-152	-302	-362	-272	-272
Configuration	MOB	FTL	FTL	MOB	MOB	FTL	FTL

Table 5 – In-track spacing, in seconds, of GDC observatories relative to reference observatories (denoted by blue zeroes) by mission phase. In "MOB" configuration, G2 is the reference observatory and all in-track spacings are referenced to it. In "FTL" spacing, G2 is the reference observatory for the "Green Team" (G2, G5, and G6), and G4 is the reference observatory for the "Red Team" (G1, G3, and G4). G4 is either drifting relative to G2 (phases 1b, 2a, 3c) or fixed at half an orbit period from G2 (phase 3b).

essentially the same geodetic altitude every time they fly over the same latitude. This is shown in **Figure 6** where we have 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 getting these ephemerides simulated promptly and out to the community, 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 6**). Therefore, there are no drag make-up maneuvers 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 caused by differential drag as the observatories deplete fuel at different rates but that was not modeled here. Proposers should assume that the altitude vs latitude curve for all six observatories will move through the family of curves in **Figure 6** every few months before the constellation is reboosted to the top of the altitude corridor.

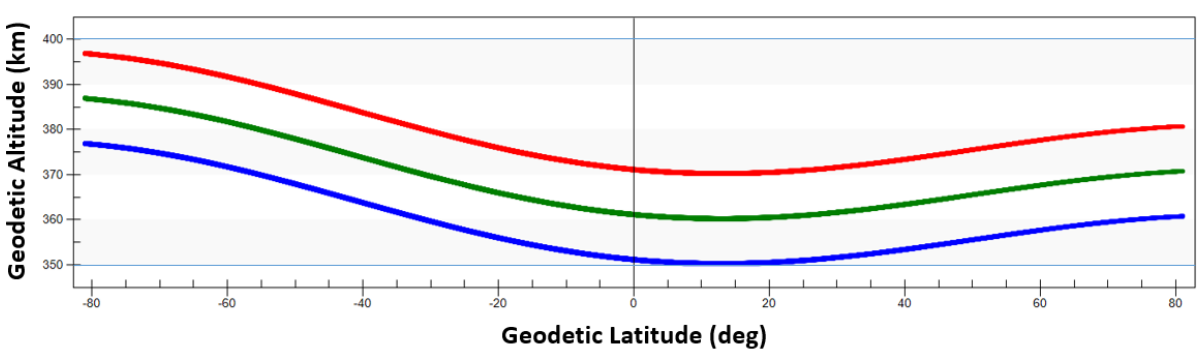

Figure 6-- The geodetic altitude vs geodetic latitude for the "frozen orbits" of the GDC constellation. Each observatory will start with the red curve, at the top of the altitude corridor, and over the span of a few months will lose energy due to orbital drag, reaching the altitude/latitude profile shown by the blue curve. When this occurs, the observatory will be boosted in altitude back to the altitudes shown in the red curve.

2.5 Detailed description of the DRM Phases

2.5.1 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 proposed investigations should not plan to use data during this period (though initial calibration data may 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 7** 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.

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.

Figure 7 -- 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.

2.5.2 Phase 1: Local-scale observations **Day 91-290**

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. **Table 5** shows the "synchronicity" of the observatories (the time delay from when a reference observatory, typically G2, crosses a given latitude (on the ascending leg), until the other observatories cross the same latitude on the ascending leg.

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, in order to allow the most complete sampling of spatial and temporal scales of interest:

- Phase 1a -- "Local-Fast" 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
- Phase 1b – "Local-Slow" phase, which provides measurements of local-scale spatial structures and their time variation on timescales ranging from a few minutes to half an orbit period (~47 minutes)

These two sub-phases are distinguished by the "in-track" spacing of the observatories. Changes in this spacing results in two qualitatively different approaches, which are complementary and necessary to explore the full range of spatio-temporal scales. The same general plan will also be used in Phases 2 and 3, described below.

Figure 8 -- The constellation configuration at the beginning of Phase 1a ("Local-fast"), where the maximal LTAN separation between orbit planes is 12.8°. The format is the same as in Figure 7.

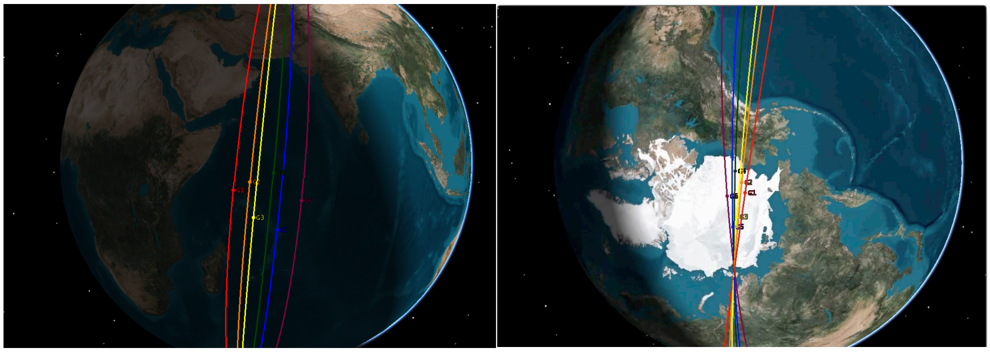

Figure 9 – Representative examples of the relative positioning of the six observatories during Phase 1a near the equator (left) and near the pole (right). This configuration is referred to as a "MOB" (multiple overlapping baselines), and it provides well-constrained measurements of spatial variation, as well as measurements of rapid temporal variation.

<u>Phase 1a: "Local-Fast" scale, using Multiple Overlapping Baselines (MOB)</u> **Days 91-190**

In Phase 1a, the observatories are spaced close together "in-track" (see **Table 5**), with fixed relative phasings. The orbit planes are still close together (**Figure 4**). This mission phase is designed to provide "multiple overlapping baselines" to strongly constrain spatial variations at "local" scales (a few hundred to a few thousand km). Triangular baselines, each formed from a different set of three observatories (twenty in all) can be used to estimate latitudinal and longitudinal gradients and assess spatial variations of parameters of interest to GDC. This close spacing also permits assessment of temporal changes that occur faster than ~3 minutes. Over the 100 days of Phase 1a, this configuration will precess through the full range of local times. **Figure 8** shows the configuration of the orbit planes at the beginning of this phase (from day 91). **Figure 9** shows a representative example of the relative position of the six observatories near the equator (left) and pole (right).

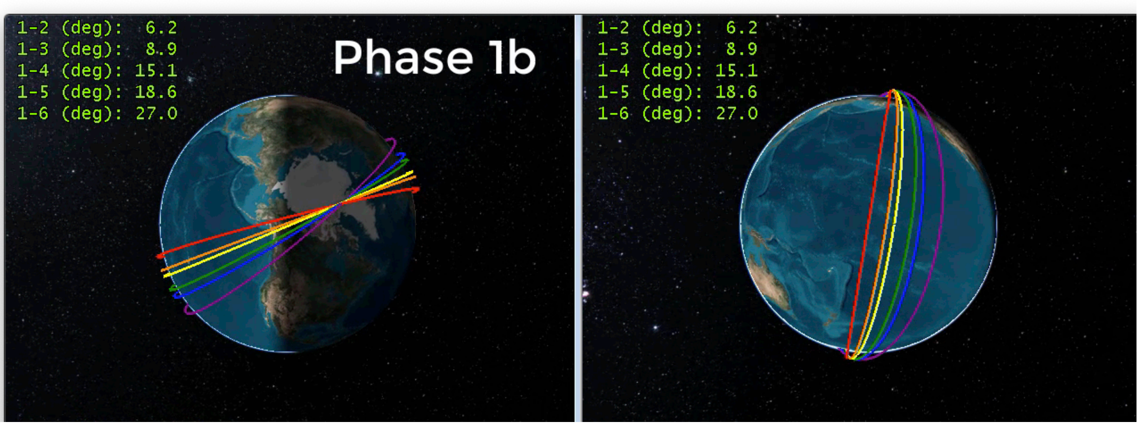

Figure 10 – The constellation configuration at the beginning of Phase 1b ("Local-slow"), where the maximal LTAN separation between orbit planes is 27°. The format is the same as in Figure 7.

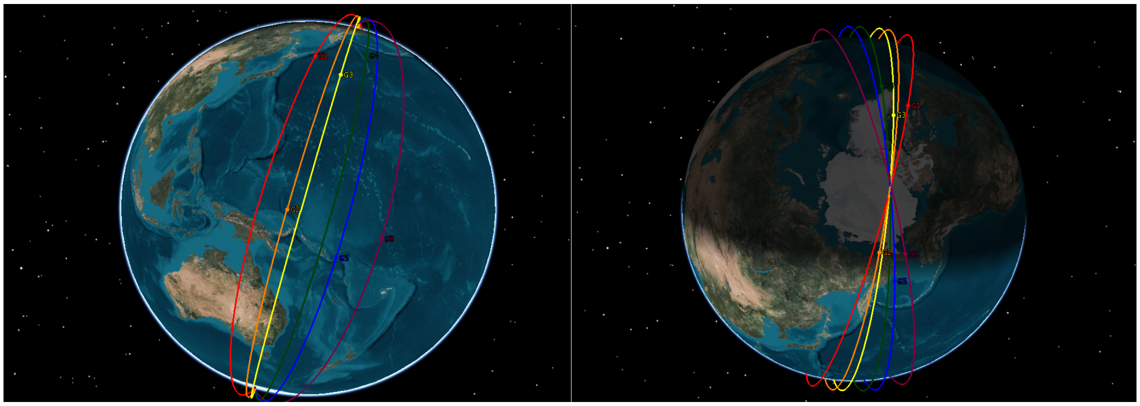

Figure 11 – Representative examples of the relative positioning of the six observatories during Phase 1b near the equator (left) and near the pole (right). This configuration is referred to as "FTL" ("follow the leader"), and it provides measurements of spatial variation, as well as measurements of slower temporal variation, on timescales from several minutes to half an orbit period and beyond.

<u>Phase 1b: "Local-Slow" scale, using Follow The Leader (FTL)</u> **Days 191-290**

Figure 10 and **Figure 11** show the orbit plane spacing and representative positions for the observatories in Phase 1b. 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.

In Phase 1b, the observatories are divided into two "teams", each with three observatories. These teams ("red team" – G1, G3, G4 and "green team" – G2, G5, G6) are held at fixed in-track spacings within a given team. The two teams are, however, in orbits with slightly different semi-major axes (SMAs) – with the red team about 3 km lower than the green team. Over time, this

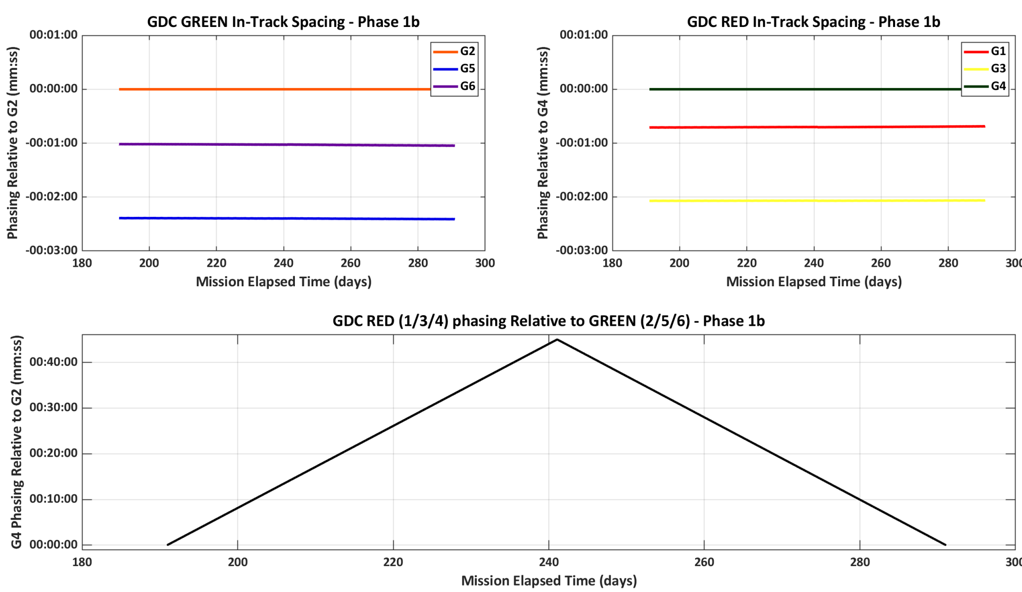

Figure 12 – The "in-track" separation between observatories in Phase 1b. G2, G5, G6 for the "green team", with fixed orbit phase separations between them, and G1, G3, and G4 form the "red team" with a different set of fixed orbit phase separations. The bottom panel shows the relative separation between red (leading) and green (lagging), and it shows that this grows to ½ orbit and then back to zero.

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. 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 3 minutes and half an orbit period.

At this rate of drift, the red team is ½ orbit ahead of green after 50 days. At this time, the red team's SMA is increased to be 3 km over the green team, and the relative in-track drift reverses until after another 50 days the two teams are cross the same latitude with no time delay.

This scheme is chosen because the red team is slightly west of 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.

The "Phase 1b" column in **Table 5** shows the relative spacing of each member in a given team relative to its reference observatory (G2 for "green" team, G4 for "red" team). The relative spacings between the observatories are shown graphically in **Figure 12**. Over the 100 days of Phase 1b, this configuration will precess through the full range of local times **Figure 13** shows a sequence of positions of the green and red team during an interval where the observatories are crossing the northern high latitude region, on day 241 of the mission (where the two "teams" are phased nearly half an orbit apart), plotted as latitude vs longitude (left) or latitude vs local time (right), demonstrating how the FTL configuration provides good spatial overlap (in a frame corotating with the Earth) between subsequent sampling even with delays of up to 45 minutes. The local time overlap is also excellent.

At the end of the 200-day Phase 1, maneuvers adjust the constellation to prepare for the beginning of Phase 2, where the constellation will gather both local and regional-scale data.

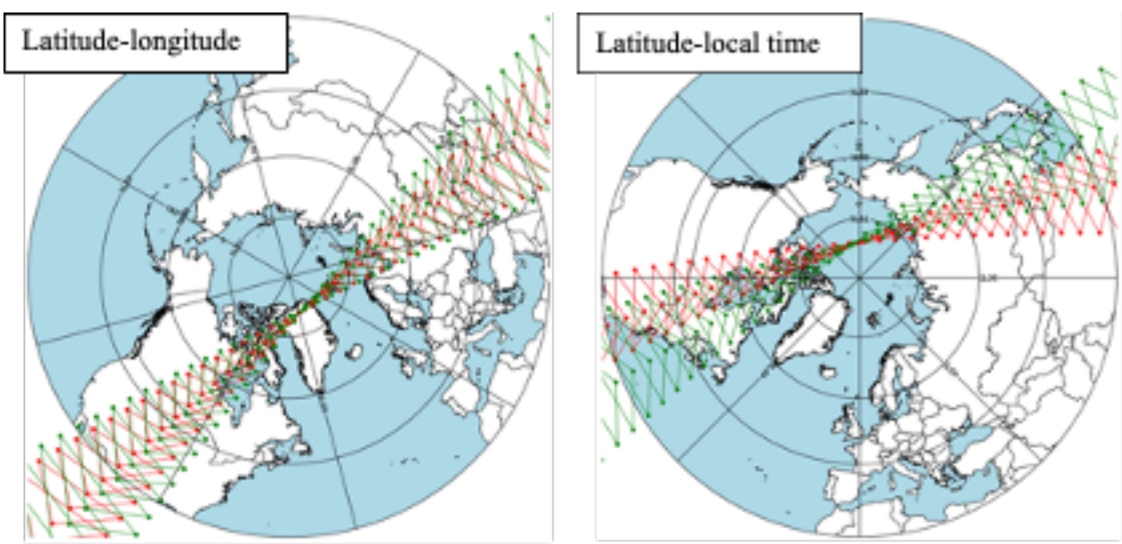

Figure 13 – A sequence of observatory locations for the green and red "teams" (represented at each instant by a triangle connecting the three team members – multiple time points are overplotted here to show how the team configuration evolves with latitude), for day 241 of the mission (red-green separation is nearly one half orbit). Left: northern high latitude region, with the subsatellite points plotted as latitude and longitude. Right: the subsatellite points plotted as latitude and local time. (continent outlines for reference).

2.5.3 Phase 2: Regional-scale observations **Day 291-425**

Phase 2 marks the interval when the LTAN spacing of the orbit planes (**Figure 4**) has increased to provide enough separation to enable "regional-scale" measurements (several thousand km scale), and spanning nearly 3 hours in local time early in Phase 2. Because some of the orbit planes have smaller separations, GDC will also make "local-scale" measurements during this mission phase.

As before, **Table 5** shows the "synchronicity" of the observatories (the time delay from when a reference observatory, typically G2, crosses a given latitude (on the ascending leg), until the other observatories cross the same latitude on the ascending leg. The Phase 2 spacings are approximately double what they were in Phase 1.

During all of Phase 2, 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 ~100 days.

Phase 2 is divided into two subphases, in order to allow the most complete sampling of spatial and temporal scales of interest:

- Phase 2a -- "Regional-Slow" phase, which provides measurements of regional-scale spatial structures and their time variation on timescales ranging from a few minutes to half an orbit period (~47 minutes)
- Phase 2b – "Regional-Fast" phase, which strongly constrains regional- and local-scale spatial structures while permitting studies of time variations of these structures on timescales of 30 seconds up to a few minutes

Phase 2a: "Regional-Slow" scale, using Follow The Leader (FTL) **Days 291-390**

Figure 14 and **Figure 15** show the orbit plane spacing and representative positions for the observatories in Phase 2a. As in Phase 1a, 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

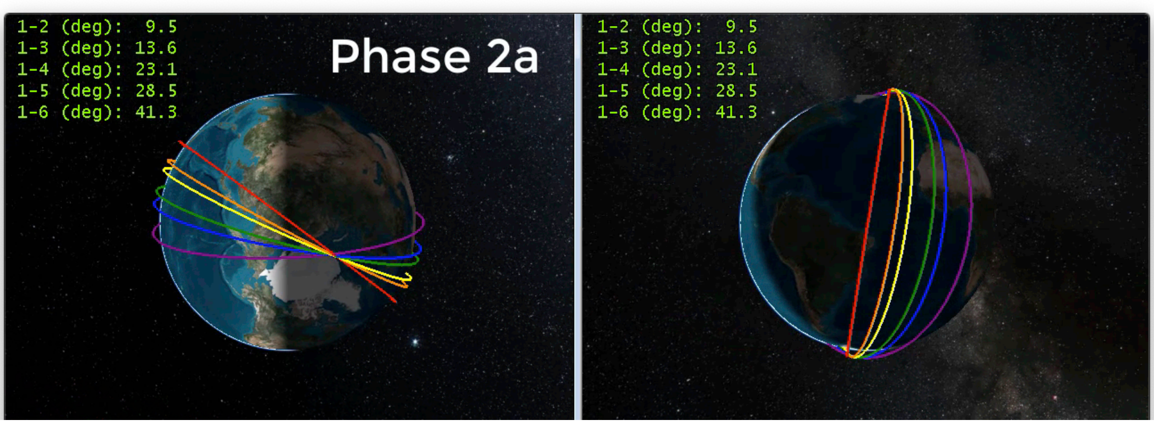

Figure 14 – The constellation configuration at the beginning of Phase 2a ("Regional-slow"), where the maximal LTAN separation between orbit planes is 41.3°. The format is the same as in Figure 7.

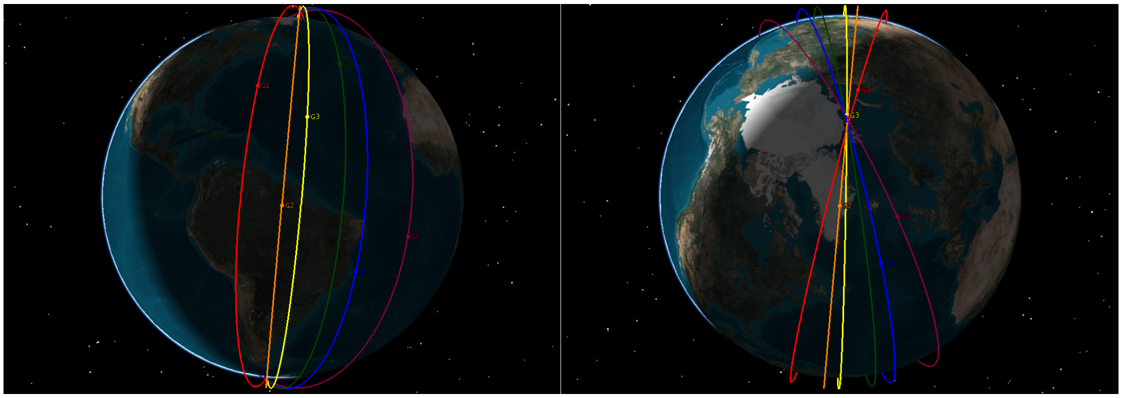

Figure 15 – Representative examples of the relative positioning of the six observatories during Phase 2a near the equator (left) and near the pole (right). This configuration is referred to as "FTL" ("follow the leader"), and it provides measurements of spatial variation, as well as measurements of slower temporal variation, on timescales from several minutes to half an orbit period and beyond.

period and beyond. Due to the larger spread in LTAN of the orbit planes, and the larger in-track spacings, Phase 2a will focus on larger spatial scale sizes than Phase 1b. **Figure 16** shows the in-track spacing, graphically, as a function of time during Phase 2a.

Similarly to Phase 1b, Phase 2a is in an "FTL" configuration, with one "team" of three observatories slowly scanning in in-track separation over the course of 50 days until it reaches half an orbit phase shift. At that point, a maneuver adjusts the semimajor axes of the orbits to bring the teams back into alignment at the end of Phase 2a.

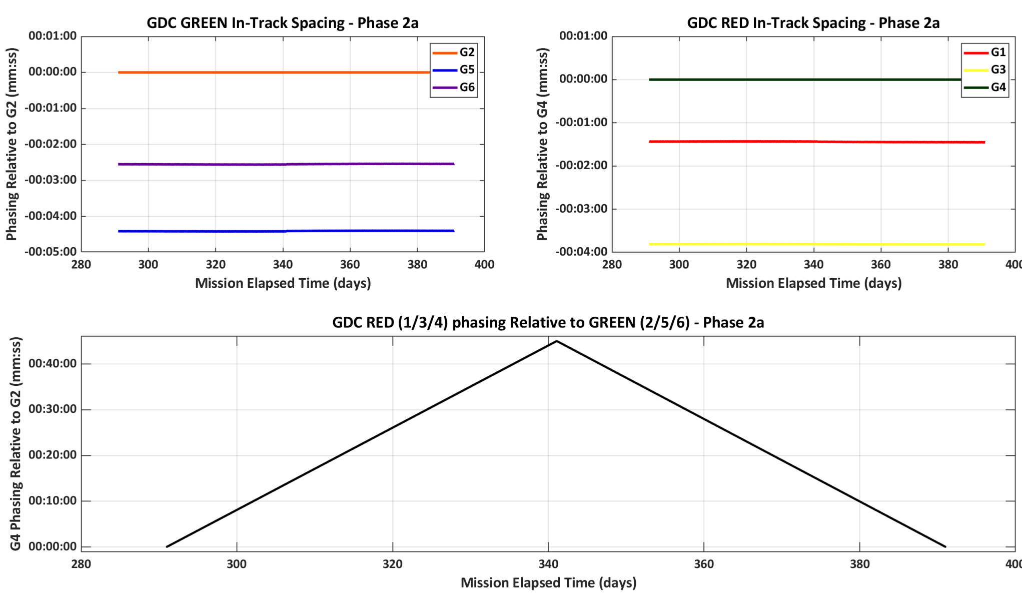

Figure 16 – The "in-track" separation between observatories in Phase 2a. G2, G5, G6 for the "green team", with fixed orbit phase separations between them, and G1, G3, and G4 form the "red team" with a different set of fixed orbit phase separations. The bottom panel shows the relative separation between red (leading) and green (lagging), and it shows that this grows to ½ orbit and then back to zero during Phase 2a.

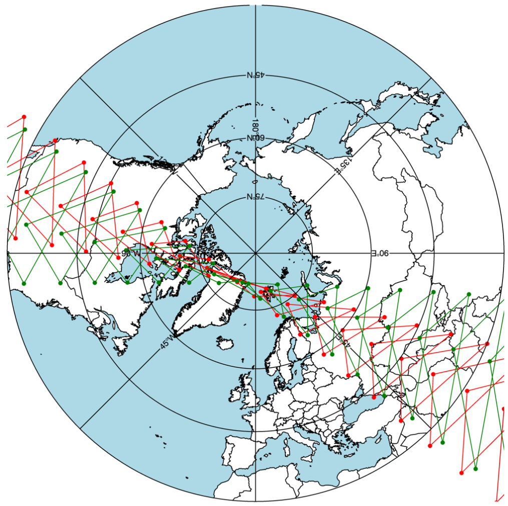

Figure 17 – A sequence of observatory locations for the green and red "teams" (represented at each instant by a triangle connecting the three team members – multiple time points are overplotted here to show how the team configuration evolves with latitude), for day 420 of the mission (red-green separation is nearly one half orbit). Shown: northern high latitude region, with the subsatellite points plotted as latitude and longitude.

Over the 100 days of Phase 2a, this configuration will precess through the full range of local times **Figure 17** shows a sequence of positions of the green and red team during an interval where the observatories are crossing the northern high latitude region, on day 420 of the mission (where the two "teams" are phased nearly half an orbit apart), plotted as latitude vs longitude, demonstrating how the FTL configuration provides good spatial overlap (in a frame corotating with the Earth) between subsequent sampling even with delays of up to 45 minutes.

At the end of the 100-day Phase 2a, maneuvers adjust the constellation to prepare for the beginning of Phase 2b, where the constellation will gather both local and regional-scale data in the "MOB" configuration.

<u>Phase 2b: "Regional-Fast" scale, using Multiple Overlapping Baselines (MOB)</u> **Days 391-425**

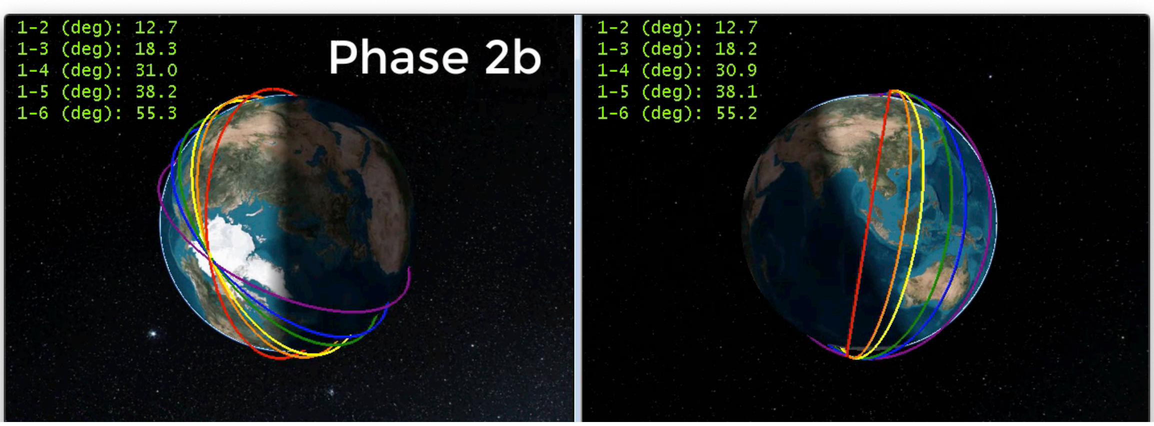

Figure 18 – The constellation configuration at the beginning of Phase 2b ("Regional-fast"), where the maximal LTAN separation between orbit planes is 55.2°. The format is the same as in Figure 7.

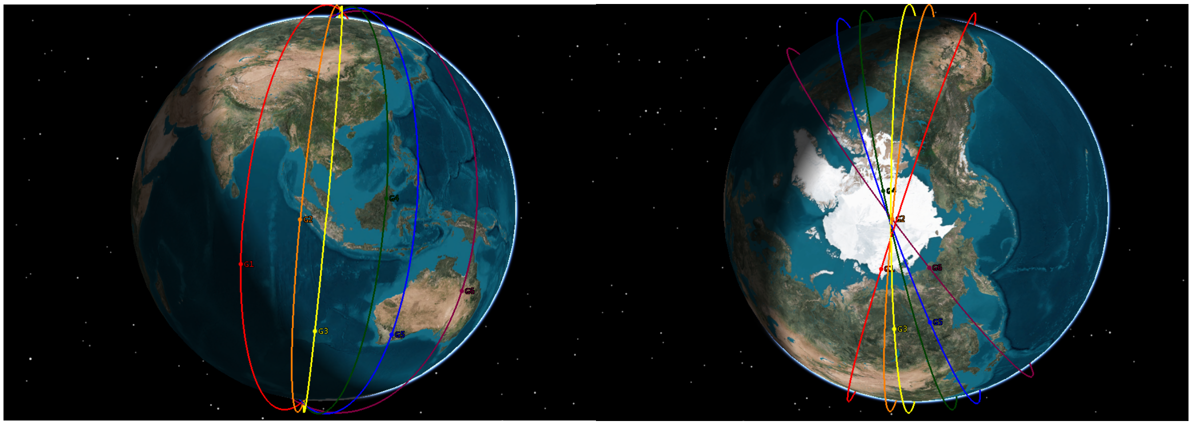

Figure 19 – Representative examples of the relative positioning of the six observatories during Phase 2b near the equator (left) and near the pole (right). This configuration is referred to as a "MOB" (multiple overlapping baselines), and it provides well-constrained measurements of spatial variation, as well as measurements of rapid temporal variation.

In Phase 2b, the observatories are spaced close together "in-track" (see **Table 5**), with fixed relative phasings. The orbit planes have drifted apart, to a regional-scale separation (see **Figure 4**). This mission phase is designed to provide "multiple overlapping baselines" to strongly constrain spatial variations at "regional and local" scales (a few hundred to a few thousand km). Triangular baselines, each formed from a different set of three observatories (twenty in all) can be used to estimate latitudinal and longitudinal gradients and assess spatial variations of parameters of interest to GDC. This close spacing also permits assessment of temporal changes that occur faster than ~3 minutes. Over the 35 days of Phase 2b, this configuration will precess through about half the full range of local times. **Figure 18** shows the configuration of the orbit planes at the beginning of this phase (from day 391). **Figure 19** shows a representative example of the relative position of the six observatories near the equator (left) and pole (right).

At the end of Phase 2b, the in-track spacings are adjusted slightly (see **Table 5**) but the constellation remains in "MOB" formation, to prepare for Phase 3a.

2.5.4 <u>Phase 3: Global-scale observations</u> **Day 426-1094**

Phase 3 marks the interval when the LTAN spacing of the orbit planes (**Figure 4**) have increased to provide enough separation to enable "global-scale" measurements, spanning nearly 4 hours in local time early in Phase 3. Because some of the orbit planes have smaller separations, GDC will also make "local-scale" and "regional-scale" measurements during this mission phase.

As before, **Table 5** shows the "synchronicity" of the observatories (the time delay from when a reference observatory, typically G2, crosses a given latitude (on the ascending leg), until the other observatories cross the same latitude on the ascending leg. The Phase 3 spacings are larger than they were in Phase 2.

During the first part of phase 3 (phases 3a and 3b), 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 ~100 days. In the final portion of phase 3 (phase 3c) the inclination of the orbit planes is adjusted to "freeze" the constellation and stop the differential precession, though the overall secular LTAN precession continues.

Phase 3 is divided into three subphases, in order to allow the most complete sampling of spatial and temporal scales of interest:

- Phase 3a -- "Global-slow" phase, which strongly constrains global-scale spatial structures while permitting studies of time variations of these structures on timescales of an orbit period (~97 minutes) and longer
- Phase 3b – "Global-fast-fixed" phase, which provides measurements of global-scale spatial structures and their time variation on timescales of half an orbit period (~47 minutes)
- Phase 3c – "Global-fast-scanning" phase, which provides measurements of global-scale spatial structures and their time variation on timescales of several minutes up to half an orbit period

Phase 3a: "Global-Slow" scale, using Multiple Overlapping Baselines (MOB) **Day 426-764**

In Phase 3a, the observatories are spaced close together "in-track" (see **Table 5**), with fixed relative phasings. The orbit planes have drifted apart, to a global-scale separation (see **Figure 4**). This mission phase is designed to provide "multiple overlapping baselines" to strongly constrain spatial variations at "regional and global" scales (a few thousand km and larger). Triangular baselines, each formed from a different set of three observatories (twenty in all) can be used to estimate latitudinal and longitudinal gradients and assess spatial variations of parameters of interest to GDC. In addition, the first "truly global" measurements will be provided in this phase, as the orbit planes expand beyond 4 hours of LTAN separation. The close in-track spacing also permits assessment of regional-scale temporal changes that occur faster than ~3 minutes. Global-scale temporal changes can be measured on orbital period timescales. Over the 100 days of Phase 3a, this configuration will precess through the full range of local times. **Figure 20** shows the configuration of the orbit planes at the beginning of this phase (from day 391). **Figure 21** shows

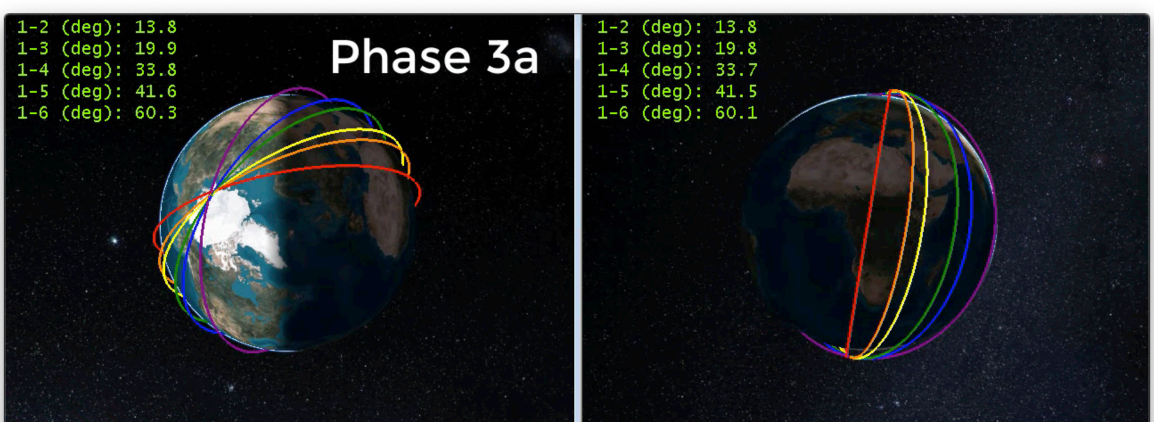

Figure 20 – The constellation configuration at the beginning of Phase 3a ("Global-slow"), where the maximal LTAN separation between orbit planes is 60.1°. The format is the same as in Figure 7.

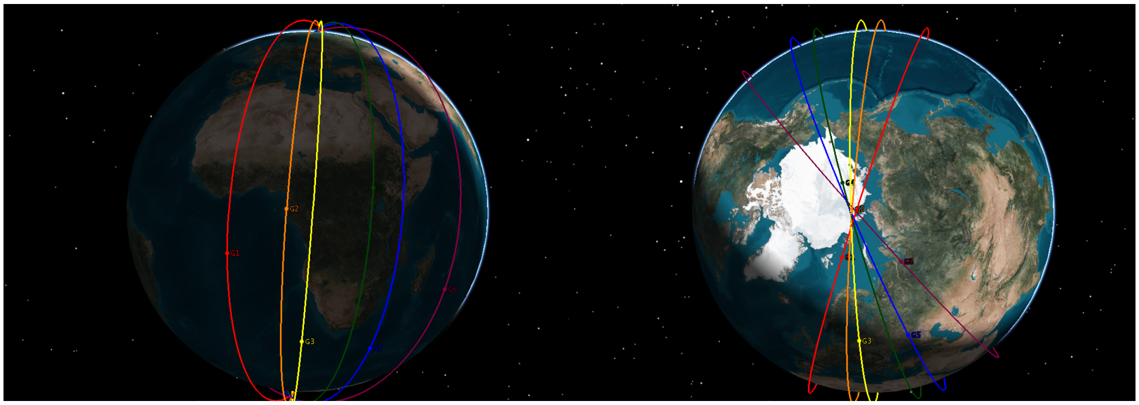

Figure 21 – Representative examples of the relative positioning of the six observatories during Phase 3a near the equator (left) and near the pole (right). This configuration is referred to as a "MOB" (multiple overlapping baselines), and it provides well-constrained measurements of spatial variation, as well as measurements of rapid temporal variation.

a representative example of the relative position of the six observatories near the equator (left) and pole (right).

At the end of Phase 3a, maneuvers are performed to put the configuration in an "FTL" configuration, similar to Phases 1b and 2a, but with one difference – the two teams do not "scan" in in-track separation, but are fixed at half an orbit, to provide some dedicated observing time at a global scale, at ~45 minute time resolution.

Phase 3b: "Global-fast-fixed" scale, using Follow the Leader (FTL) **Day 764-829**

Figure 22 and **Figure 23** show the orbit plane spacing and representative positions for the observatories in Phase 3b. As in Phase 3a, the focus is on measuring spatial gradients but also permitting assessment of slower rates of change, in this case fixed at half an orbit period, in order to make more highly resolved measurements of time variations. **Figure 24** shows the in-track spacing, graphically, as a function of time during Phase 3b.

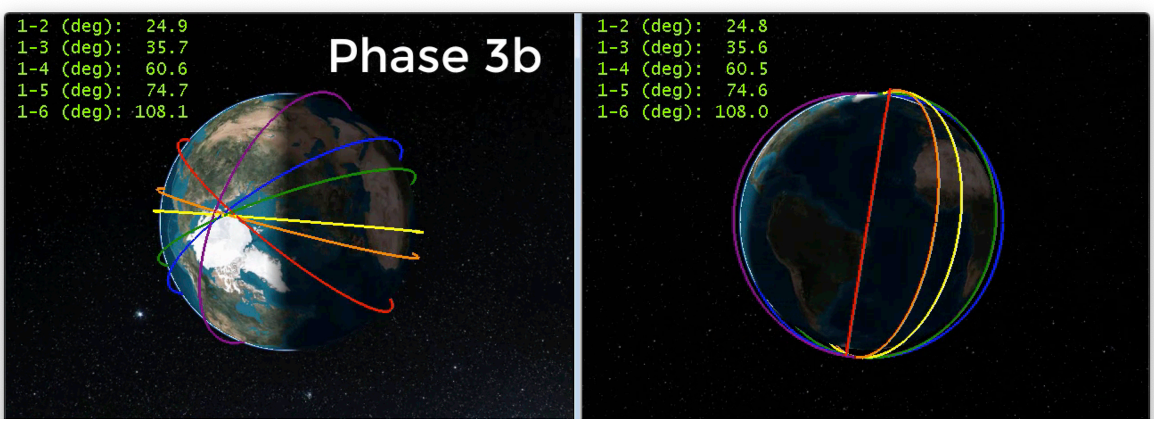

Figure 22 – The constellation configuration at the beginning of Phase 3b ("Global-fast-fixed"), where the maximal LTAN separation between orbit planes is 108°. The format is the same as in Figure 7.

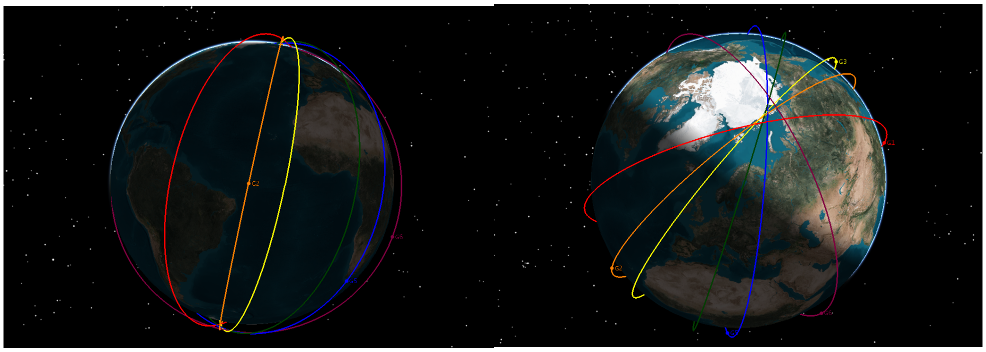

Figure 23 – Representative examples of the relative positioning of the six observatories during Phase 3b near the equator (left) and near the pole (right). This configuration is referred to as a "MOB" (multiple overlapping baselines), and it provides well-constrained measurements of spatial variation, as well as measurements of rapid temporal variation.

Similarly to Phase 1b, Phase 3b is in an "FTL" configuration, with one "team" of three observatories half an orbit out of phase with the other. In this phase, unlike Phase 1b, the two teams do not "scan" in orbit phase, but are maintained at a fixed phase difference of one half orbit.

At the end of Phase 3b, two maneuvers are performed – one to equalize the inclinations of the six orbit planes, to null out the differential LTAN separation (see **Figure 4**). This will "freeze" the constellation configuration in relative LTAN, even as the whole constellation precesses in local time (see **Figure 5**). The other maneuver "unfreezes" the in-track "synchronicity" of the two teams and lets them "scan" over a range of in-track synchronicities, similar to Phases 1b and 2a.

<u>Phase 3c: "Global-fast-scanning" scale, using Follow the Leader (FTL)</u> **day 829-1024**

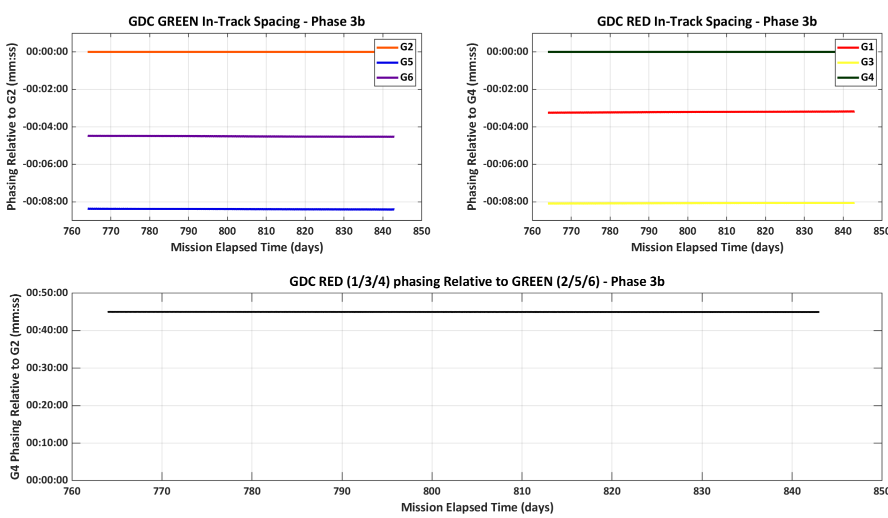

Figure 24 – The "in-track" separation between observatories in Phase 3b. G2, G5, G6 for the "green team", with fixed orbit phase separations between them, and G1, G3, and G4 form the "red team" with a different set of fixed orbit phase separations. The bottom panel shows the relative separation between red (leading) and green (lagging), and it shows that this is fixed at ½ orbit.

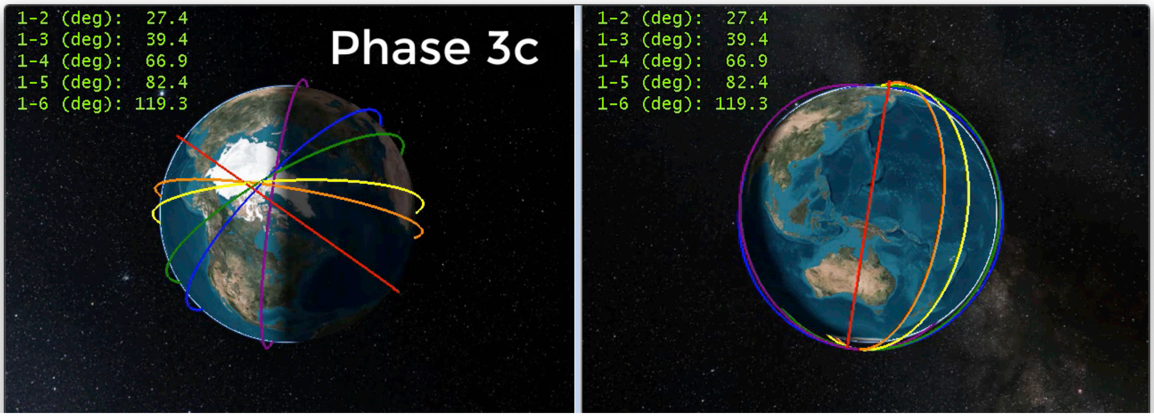

Figure 25 – The constellation configuration at the beginning of Phase 3c ("Global-fast-scanning"), where the maximal LTAN separation between orbit planes is 119.3°. The format is the same as in Figure 7.

Figure 25 and **Figure 26** show the orbit plane spacing and representative positions for the observatories in Phase 3c. As in Phase 3b, the focus is on measuring spatial gradients but also permitting assessment of slower rates of change, in this case scanning through all inter-team separations rather than being fixed at half an orbit, similar to Phases 1b and 2a. Unlike those phases, there is no maneuver to "unwind" the scan, and it is allowed to proceed for the remainder of the phase. **Figure 27** shows the in-track spacing, graphically, as a function of time during Phase 3c.

At the end of Phase 3c, the observatories will undergo a controlled de-orbit, or, if approved by NASA HQ, will maneuver to support an extended science mission.

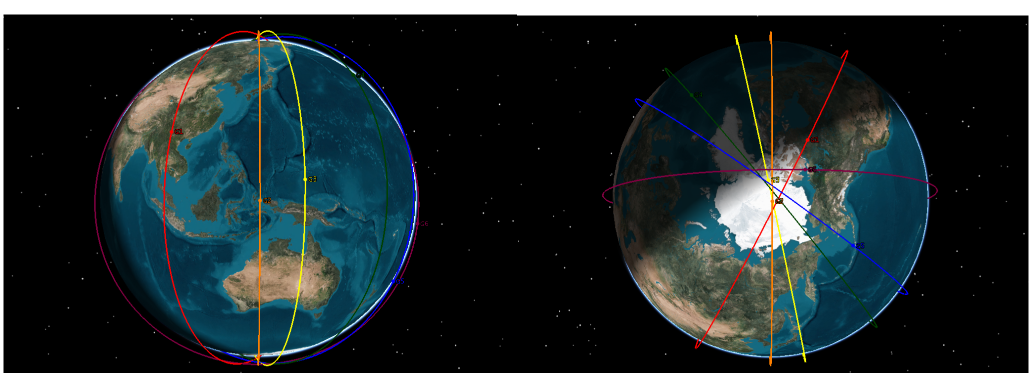

Figure 26 – Representative examples of the relative positioning of the six observatories during Phase 3c near the equator (left) and near the pole (right).

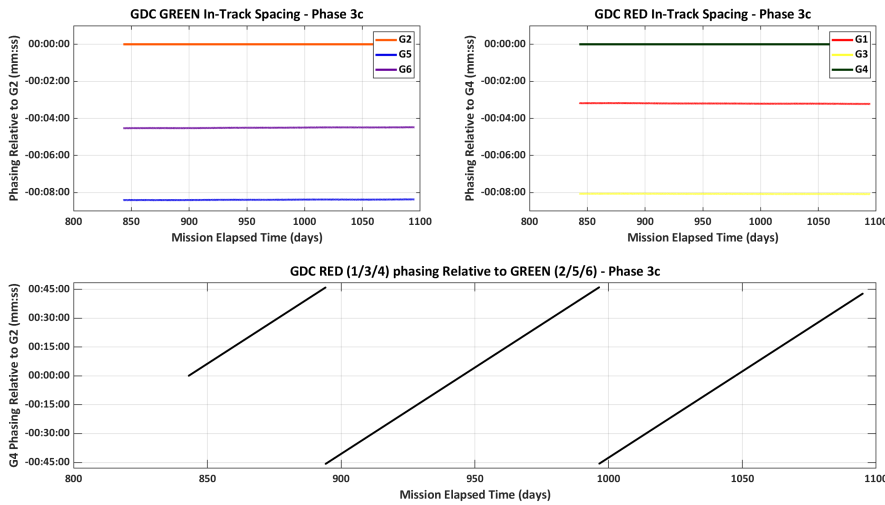

Figure 27 – The "in-track" separation between observatories in Phase 3c. G2, G5, G6 for the "green team", with fixed orbit phase separations between them, and G1, G3, and G4 form the "red team" with a different set of fixed orbit phase separations. The bottom panel shows the relative separation between red (leading) and green (lagging), and it shows that this grows from 0 to ½ orbit to a full orbit and and then wraps around.

2.6 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

There is a movie in the .zip archive that contains the ephemeris files (**GDC_Constellation_v3.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_Phase1b_FTL.mp4**) that shows the motion of the observatories during the Phase 1b Follow The Leader (FTL) scenario. The movie shows the six GDC orbit planes, with triangles highlighting the two separate teams: Red (G1/G3/G4) and Green (G2/G5/G6). The movie was created "stop-motion" style by capturing an image at every ascending node of G2. As such, it appears that the GREEN trio doesn't move, as the RED trio advances ahead of GREEN. The data overlay "G4 Phase" represents how far G4 is ahead of G2. The "G4 Phase" will reach close to 180 degrees (a half-orbit) before it begins to decrease because the two trios swapped altitudes. Then, the RED trio will begin to move backwards towards the GREEN trio until they are in sync at the end of Phase 1b. Similar behavior is exhibited in Phases 2a and 3c.

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

Sample Ephemeris Data

Time (MisElap)	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
91/00:00:00.000	-5390.990	-1724.765	-3664.336	4.344298	-0.128239	-6.338289	-33.239	-111.002	371.021	-0.614562	0.723793	0.313747	0.626254	-0.779617	-0.001754
91/00:00:30.000	-5257.535	-1727.603	-3852.299	4.551826	-0.060957	-6.191370	-35.166	-110.675	371.803	-0.614566	0.723790	0.313747	0.627958	-0.778245	-0.001759
91/00:01:00.000	-5117.934	-1728.422	-4035.746	4.753976	0.006377	-6.037236	-37.091	-110.326	372.593	-0.614570	0.723786	0.313747	0.629659	-0.776869	-0.001764
91/00:01:30.000	-4972.352	-1727.221	-4214.463	4.950514	0.073684	-5.876070	-39.012	-109.953	373.387	-0.614575	0.723782	0.313747	0.631357	-0.775490	-0.001768
91/00:02:00.000	-4820.961	-1724.002	-4388.242	5.141215	0.140887	-5.708065	-40.931	-109.552	374.183						

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
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
STDT	Science and Technology Definition Team Report
TBD	To be determined
TBR	To be revised
TBS	To be scheduled
TMC	Technical/Management/Cost review
TVB	Temporal Variation assessment Baseline