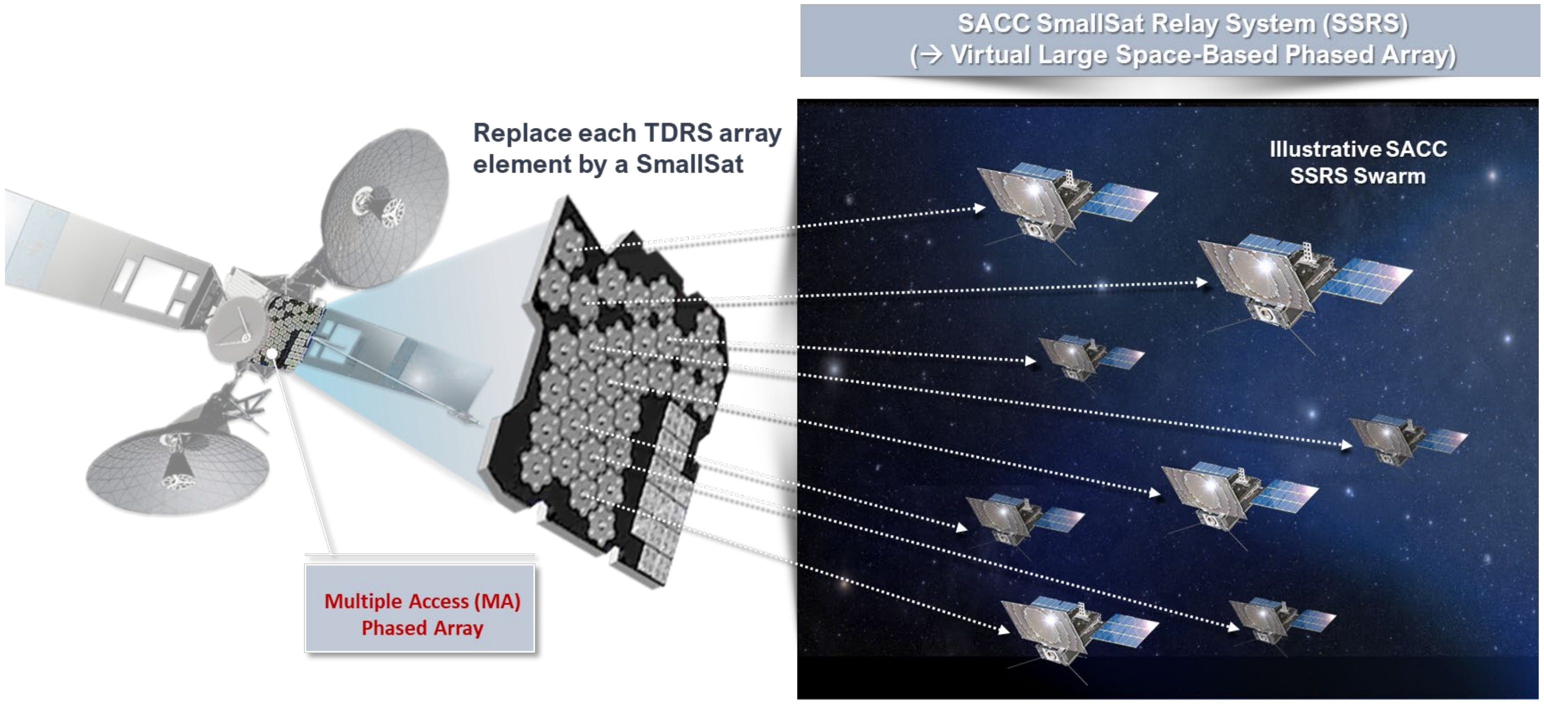
TELTRIUM

Introduction to: Swarm Array Coherent Combining (SACC) Technology*

There is wide agreement that SmallSats represent a path forward to realize enormous benefits across the entire space enterprise. In this context, there are many scientific and engineering efforts being directed to using swarms of SmallSats to accomplish ever more complex operations and replace costly, custom satellite systems.

We believe that SACC represents a viable, realizable and meaningful step forward to applying SmallSat Swarms to fulfilling a critical niche here by providing critical relay communications across the entire set of our space regimes.



Evolution away from Large Monolithic/Costly Relays to SmallSats

Over the last several years, the satellite landscape has seen the emergence of smaller and smaller satellites which we refer to here as "SmallSats". SmallSats offer many benefits including rapid deployment timeliness, robustness, and reduced costs that lend themselves to resiliency, scalability and flexibility.

These benefits have prompted interest in leveraging SmallSats to work in a 'coordinated' swarm to provide high-rate relay communications to end-receivers. However, the approach under consideration by NASA, JPL and members of the academic community has 'extreme' requirements that have proven challenging to meet. It requires all SmallSats to transmit signals in precise time/phase synchronization so that they arrive already mutually 'aligned' in phase and time at the end-receiver. This would necessitate coordinated and ongoing signal conditioning at each node prior to transmission, in addition to precise node ephemeris knowledge – a costly and complex undertaking.

This paper introduces a new technology that would use swarms of simple SmallSats for relay communications while eliminating these 'extreme' requirements.

We denote our technology as "Swarm Array Coherent Combining" and use the acronym 'SACC.'

SACC accomplishes the signal 'arraying' operation in a different way that eliminates all the node synchronization and coordination complexities noted above, while reducing SmallSat node processing requirements. In essence, all synchronization is done at the ground without imposing harsh requirements for the space segment elements and constellation.

At a high level, our innovation replaces the phased array elements that are physically attached to a traditional monolithic relay antenna by simple/uncoupled, bent-pipe SmallSats and a SACC ground signal processor.

We refer to this relay system as the SACC SmallSat Relay System (SSRS) wherein each SmallSat in the swarm is referred to as a SACC Relay SmallSat (SRS). In effect, our innovation is a virtual large space-based phased array. Our SSRS swarm size has no inherent limitations and can be populated with as many nodes as required to meet the specific requirements for a given deployment, whether it be from aeronautical to LEO/GEO to Deep Space regimes.

NASA TDRS-M

- GEO – space communications bentpipe
- Launched 18 August 2017
- S, Ku, Ka frequency bands
- 2,300 watts
- 7,614 lbs
- 15 years lifetime
- Satellite cost: $289M
- Launch cost: $134.4M

ViaSat-3

- GEO - telecommunications, regenerative
- Launched 1 May 2023; failure
- Ka-band
- 20,000 watts
- 14,109 lbs
- -- years lifetime
- Satellite Cost: $550M
- Launch Cost: $150M (estimate)

Intelsat 39 / EDRS-C

- GEO relay - telecommunications bentpipe
- Launched: August 6, 2019
- C, Ku frequency bands
- 3600 watts
- 14,550 lbs
- 15+ years lifetime
- Satellite cost: 155$M
- Launch cost: $177M (estimate)

NASA Mars Reconnaissance Orbiter

- Planetary relay + science, bentpipe
- Launched 12 Aug 2005
- X, Ka frequency bands
- 2,000 watts
- 4,810 lbs
- -- years lifetime
- Satellite cost: $416M
- Launch cost: $200M

Traditional GEO/Deep Space Relay Satellite Platforms

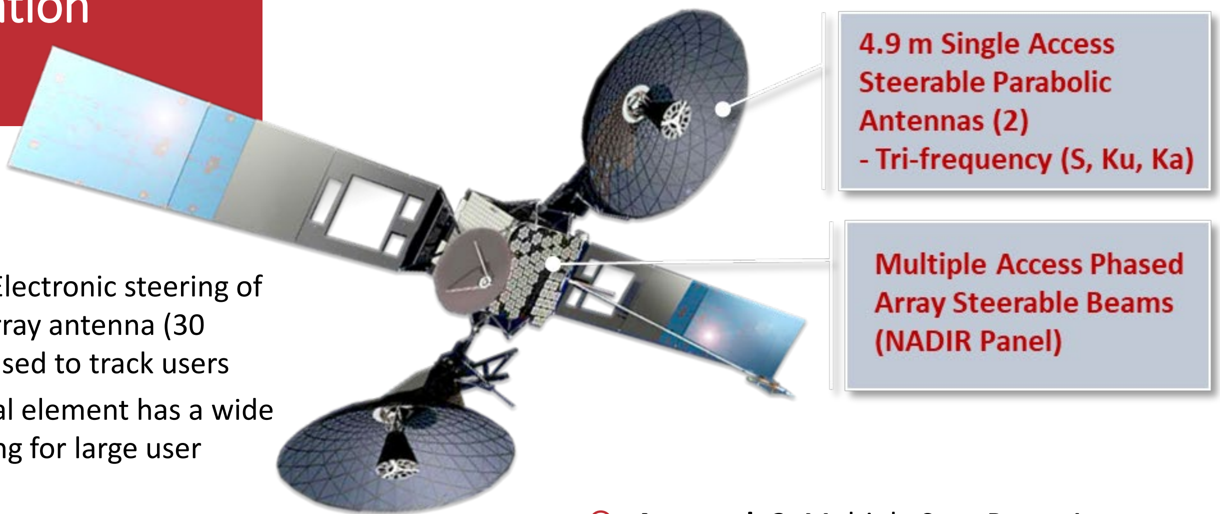
Traditionally, communications relay systems have been large monolithic and costly spacecraft supporting NASA, DoD, INTEL and commercial users.

Relay satellites placed in GEO provide a large spatial coverage for LEO/ground users. Specifically, 3 GEOs at 120 degrees spacing around the GEO orbital path afford essentially 24x7 support to these user communities.

Beyond Earth, the Mars Reconnaissance Orbiter has served as a key data relay station for other Mars science missions since 2006.

Most relays involved very large projects with long development times and very high build/launch costs. They inherently represent a very high-risk point of failure, often with little or no available redundancy. One recent example is ViaSat-3 whose large reflector failed to deploy, rendering the seven-hundred million dollar ($700,000,000) relay satellite system inoperable.

NASA TDRS Embodies 2 of the 3 Main Approaches for Relay Link Implementation



- **Approach 2:** Electronic steering of the Phased Array antenna (30 elements) is used to track users
- Each individual element has a wide beam providing for large user coverage
- TDRSS employs multiple beamformers to support many simultaneous users
- TDRSS also uses CDMA to augment the beamforming spatial discrimination in supporting many simultaneous users

- **Approach 3:** Multiple Spot Beam Antenna
- Uses a large reflector with multiple feeds
- Example: ViaSat-3

One notable relay system is NASA's Tracking and Data Relay Satellite System (TDRSS). Since the mid 1980's, NASA has successfully deployed 13 TDRS's located strategically in groups at 3 GEO nodes separated by 120 degrees.

Key challenges in designing TDRSS's link and other similar GEO relay links include:

1. Large link distances requiring large receive gain and large Tx power as the GEO altitude is ~ 36,000 Km, while LEO altitudes are 2,000 Km or less,
2. Large user spatial coverage requiring a large Field of View (FOV) of ~ 30+ deg, and
3. Support to simultaneous multiple users.

To overcome these challenges, GEOs have implemented one or more of the following approaches:

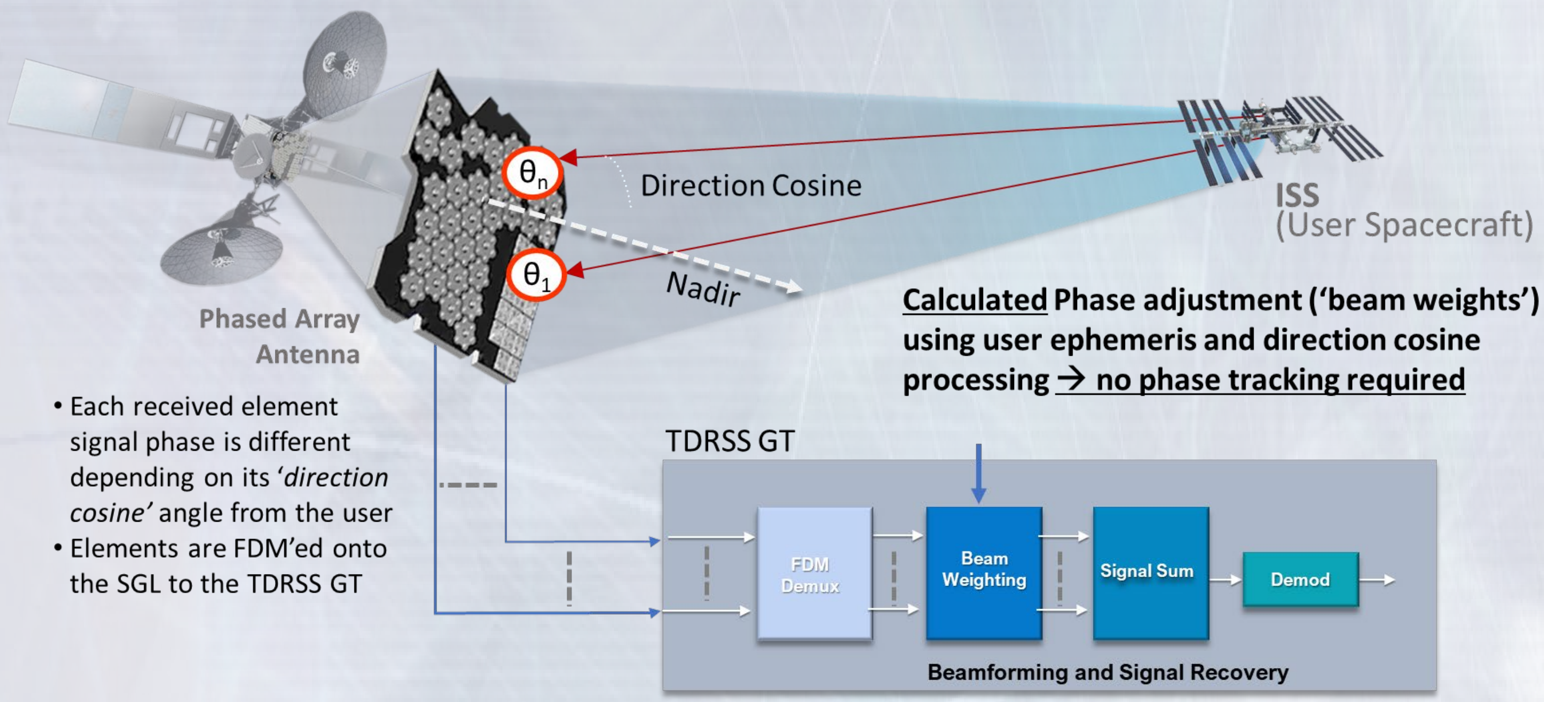
1. Large steerable antenna dishes,
2. Large electronically steered phased array antennas, and
3. Large antenna reflectors with multiple feeds to create spot beams.

As shown, a TDRS implements the first two of these three approaches above. Of special relevance for our SACC technology is the phased array. Each of the TDRS's 30 elements phased array receives its signal from a user with a slightly different phase based on its individual direction cosine from the user. These phase differences arise because of their different physical spatial locations on the array. In order to achieve the full gain of the 30 elements, these differential element signals phases have to be adjusted to align with each other to within ~ 10 degrees, so that they can be coherently summed (i.e., arrayed). When this is achieved, the TDRS array gain is 14.77 dB (=10*log(30)).

Traditional Phased Array Beamforming (e.g.,TDRSS)

Fundamental Principle:

- **Element signal phases are adjusted to be aligned in phase simply based on open-loop calculations of the differential *direction cosines***
- **This is enabled because of the known/fixed geometry of the phased array elements and user ephemeris propagation algorithms**



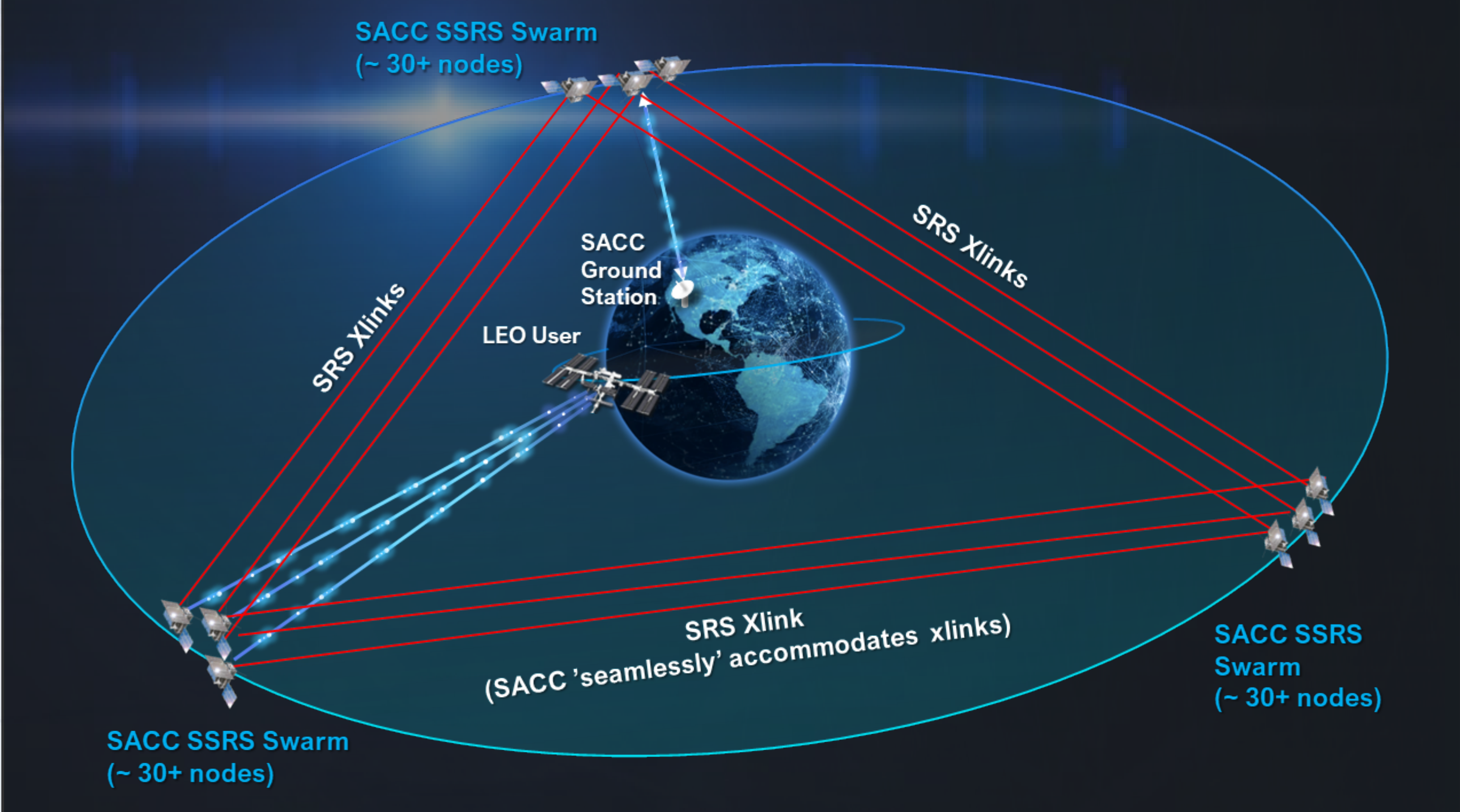
Before we further discuss our unique SACC beamforming, it is important to gain additional insight into traditional phased array beamforming wherein the array elements are attached onto an array frame structure with known and unchanging array 'geometry' like in a TDRS.

For any space-based phased array, the beamforming can be done onboard or on the ground. TDRSS has multiple generations of TDRS's where one generation is beamformed onboard, while all the others are done on the ground. Fundamentally, the signal processing and algorithms are the same.

Let's focus on the ground beamforming approach. In this architecture, the signal received by each TDRS element is bentpipe to the TDRSS ground station. These received FDM Space-to-Ground Link (SGL) signals are FDM demuxed at the ground terminal into 30 element channels.

To coherently sum these signals, their signal phases are adjusted so that they can be aligned with minimum residual differential phase. In this case, the phase differentials can be calculated simply from geometric considerations only using ephemeris knowledge/propagation of the user and the element array geometry. The linchpin here is that we have elements whose positions/location are well known --- which of course, is not what we have using uncoupled SmallSats as 'elements' in our SRSS. Note that signal demodulation occurs only after beamforming generates a signal with sufficient SNR to acquire and track the signal. The individual node signals are too noisy to support signal demodulation.

Use swarms of SmallSats at GEO separated by 120° replace Legacy Monolithic GEOs like TDRS



One Illustrative Application of using SACC Swarms (at GEO to enable 24x7 support to LEO Users)

- **Key benefits relative to legacy monolithic systems are: More Robust, Scalable, More Resilient, More Agile, Less costly to: Develop/Build, Launch, Maintain/Operate.**

We now reinforce the unique capability of GEO relays in context of our SSRS system concept which uses SmallSats instead of the traditional monolithic relays. The SRS nodes that comprise the swarm have a small antennas such that their beamwidth is commensurate with the desired FOV that reflects the spatial extent of the user community that they serve. For example, the TDRSS phased-array elements have about 26 deg beamwidth, so as to accommodate LEO orbits to ~3000 Km within its 3 dB element beamwidth.

There are other tradeoffs on any specific deployment of a SRSS architecture. These tradeoffs include the SRS aperture size/FOV, array gain, number of nodes, number of swarms and their locations. Fortunately, these tradeoffs only impact processing that is completely ground-based, allowing for relatively easy accommodation of configuration and design selections for any deployment of interest.

Consistent with recent trends, MEO and LEO relay constellations are being deployed to directly address the large pathloss for LEO to GEO links. These relay locations facilitate the ability to inherently support much higher data rates. Depending on the selection of design parameters such as user transmit power, SRS's receive antenna size, SRSS swarm size, we envision data rates in the Mbps.

Also of note is that SACC seamlessly accommodate Xlinks between SRS's to simplify the Conops and the associated ground network of support ground terminals and comm connectivity.

- Desire to simplify requirements for both:
  - Swarm Constellation and Control
  - SACC SmallSat Relay (SRS or 'node')

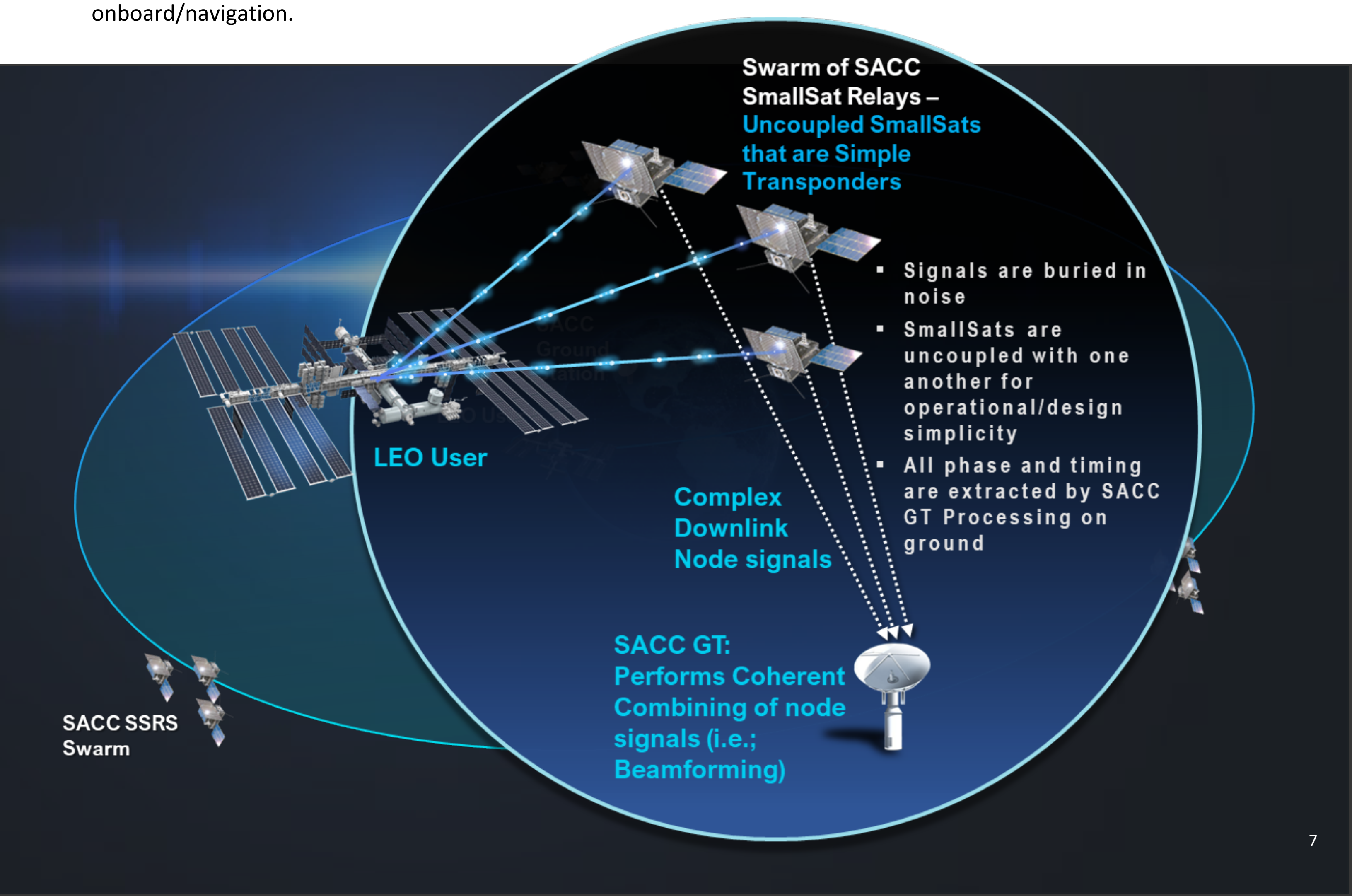
Our "SACC" Technology does just that in innovative and unique ways

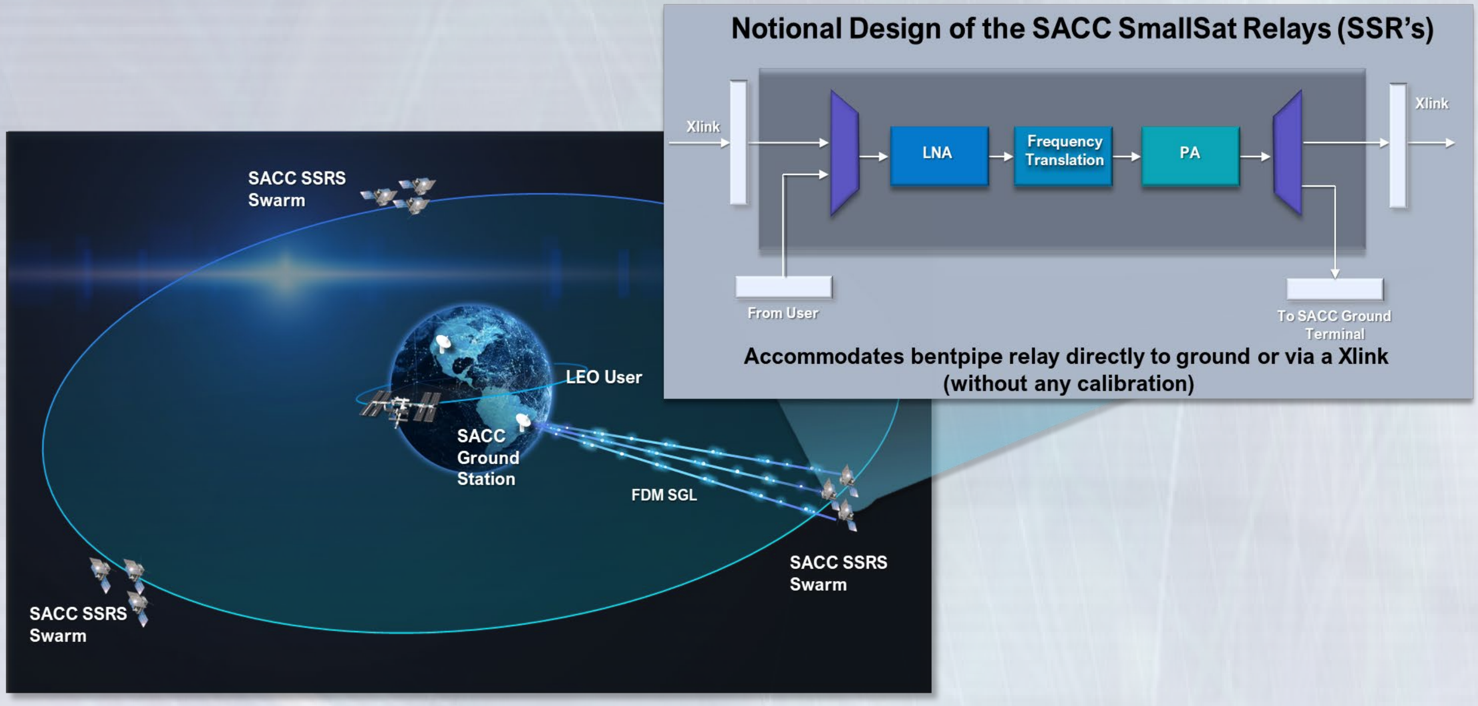
- Swarm Constellation
  - Nodes are uncoupled
  - No need to control node ephemeris
  - No need to have precise ndode ephemeris knowledge
- Swarm Nodes
  - Simple transponder (frequency translation only)
  - No onboard signal processing
  - No need for sophisticated onboard navigation
  - Low gain/wide beam antenna to eliminate antenna pointing

Critically, SACC is able to Reduce Space Segment Burden → 'Simple' Swarms and Nodes

The uniqueness of the SSRS concept is that it imposes minimal burden on the space segment. As noted, there is no need to control node ephemeris nor to have precise ephemeris knowledge of the uncoupled swarm constellation. Each swarm node is a single transponder, using a low gain/wide beam antenna to eliminate antenna pointing. Also, there are no requirements for sophisticated onboard/navigation.

In an SSRS, the user transmits its signal to the swarm constellation of nodes whereupon each node, in turn, simply bent-pipe-relays its received user signal to the ground terminal. It is then up to the novel SACC technology on the ground to deal with these node signals and ultimately array them together to form a focused high-gain sum signal for user data recovery.





- **All the complex Beamforming Functionality is off-loaded to ground processing**

Our SACC SSRS Requires only Simple Bentpipe Transponder Relays

The SRS node is a simple transponder that frequency translates the received user signal. The node downlink signals are FDM'ed on the Space-to-Ground link (SGL). As such, each node is assigned a different and specific amount of frequency translation to accomplish this FDM SGL signaling scheme.

Also, described here is the ability for an SRS to provide the received user signal not only as an SGL signal but also as a Xlink signal to another SRS at a different orbital swarm location. For simplicity, this dual functionality is represented by 2 'switches' and 2 sets of receive and transmit antennas. Both use cases retain the fundamental benefit that the SRS nodes are simple SmallSats with no onboard processing required.

Downlinks from Swarm Nodes are Complex/Nuanced Signals (that are not easily beamformed)

The SSRS node signals are quite complex and unique, thereby making our beamforming operation a seemingly daunting task. We refer to these deleterious link conditions as '**channel impairments**.'

1. The first impairment is the noise-buried signals. This is the same issue encountered by standard beamforming. It reflects the fact that each element/node signal are associated with low gain/wide beamwidth antennas to affect a large FOV for wide-spatial user coverage.

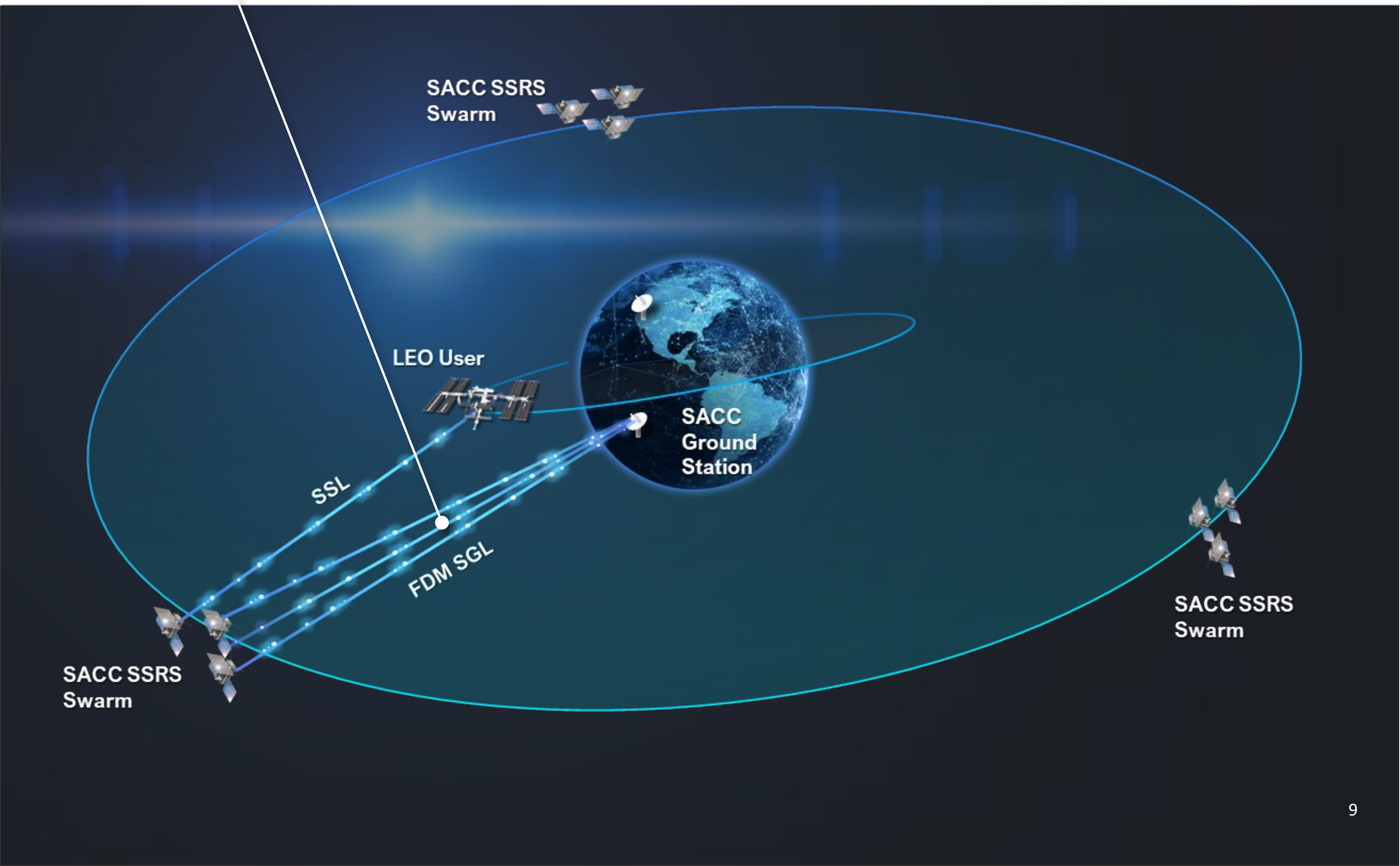
2. The second impairment is that the relative positions between the SRS nodes are dynamic and not known precisely, making their differential phases impossible to calculate with the necessary precision for coherent combining.

3. The third impairment is that each SRS has a different path length to the SACC ground terminal. These distances are also dynamic and are changing continuously. Thus, SACC beamforming requires both constant phase alignment and ongoing time alignment.

1. **Signals buried in noise**
2. **Signals are transmitted from locations that are not known precisely**
3. **Signals arrive at different times**
4. **Signals have dynamics that are not known precisely**

Beamforming requires aligning signal phases and timing

Cannot using the standard beamforming approach



Key Challenge:

How to do coherent combining on signal channels that are buried in noise and have differential Time of Arrivals (TOAs)

Our Response:

Our Swarm Array Coherent Combining (SACC) Technology addresses this challenge with two key Innovations

- **Beacon Signaling:**
  Provides node timing to allow our SACC Rx to buffer node channels accordingly

- **Feedback Signal Processing**:
  Combined/beamformed signal provides feedback of what the user data is to allow each node tracking loop to extract its phase from noise

Novel/Innovative Elements of the SACC Technology

- **Teltrium's SACC technology solves the channel impairment challenges by combining two key innovations:**

  1. **A simple beacon signaling structure on the transmitted signal.**
  2. **Feedback signal processing by the SACC ground processor to enable close loop carrier tracking.**

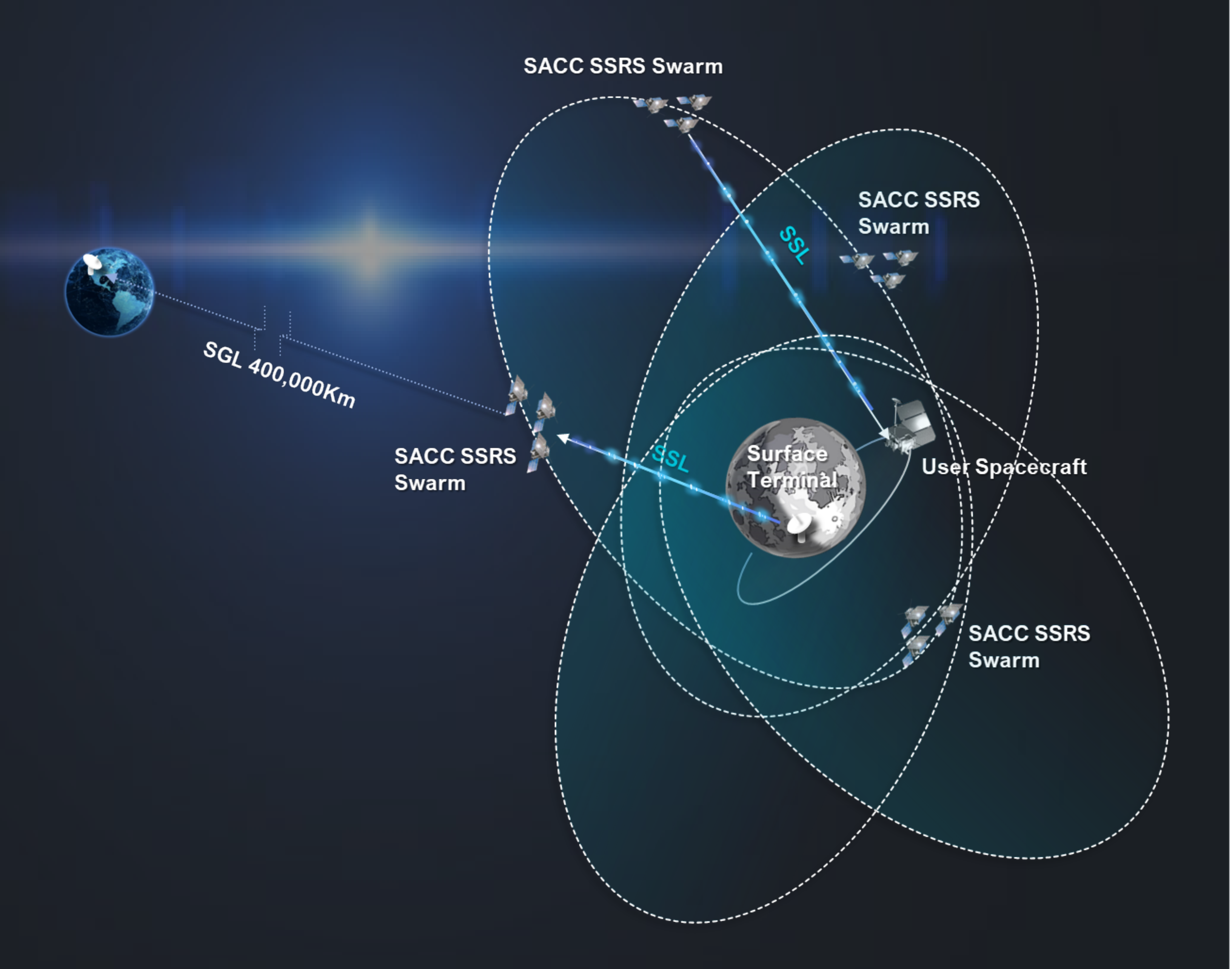
At the start of a user transmission, and before the actual Mission data is imparted onto the signal, each SRS node transmits a unique signal structure we refer to as the SACC 'Beacon' signal. The Beacon signal lasts for only a few seconds before allowing for the mission data to be sent. It consists of a PN code along with a low-rate framed-preamble that is present for a part of the Beacon signal time period. This Beacon signal enables the SACC processor to extract the differential Time-of-Arrivals (TOAs) of each node, which in turn allows for time alignment of these node signals prior to coherently combining them.

On the ground, the front-end demuxes the received FDM node signals for individual node channel processing.

At this stage, of course, the first impairment remains: each of these node channels are buried in noise so that standard carrier tracking is impossible.

Our solution draws upon a classic communications axiom. The only way to extract a signal buried in noise is to have some a prior knowledge of what the signal is. For example, PN Code Spread Spectrum ops works because the receiver has a local copy of the transmitted PN code of the received signal where every PN chip itself is buried in noise.

Akin to this, SACC leverages the fact that the output of the Array Combiner has a high SNR capture of the mission symbols that are buried in the very node signal. SACC uses the polarity of these recovered sum-signal symbols to 'extract' the node noisy symbols to feed the SACC tracking loops with high SNR signals to successfully conduct closed-loop tracking of each node phase prior to array combining.



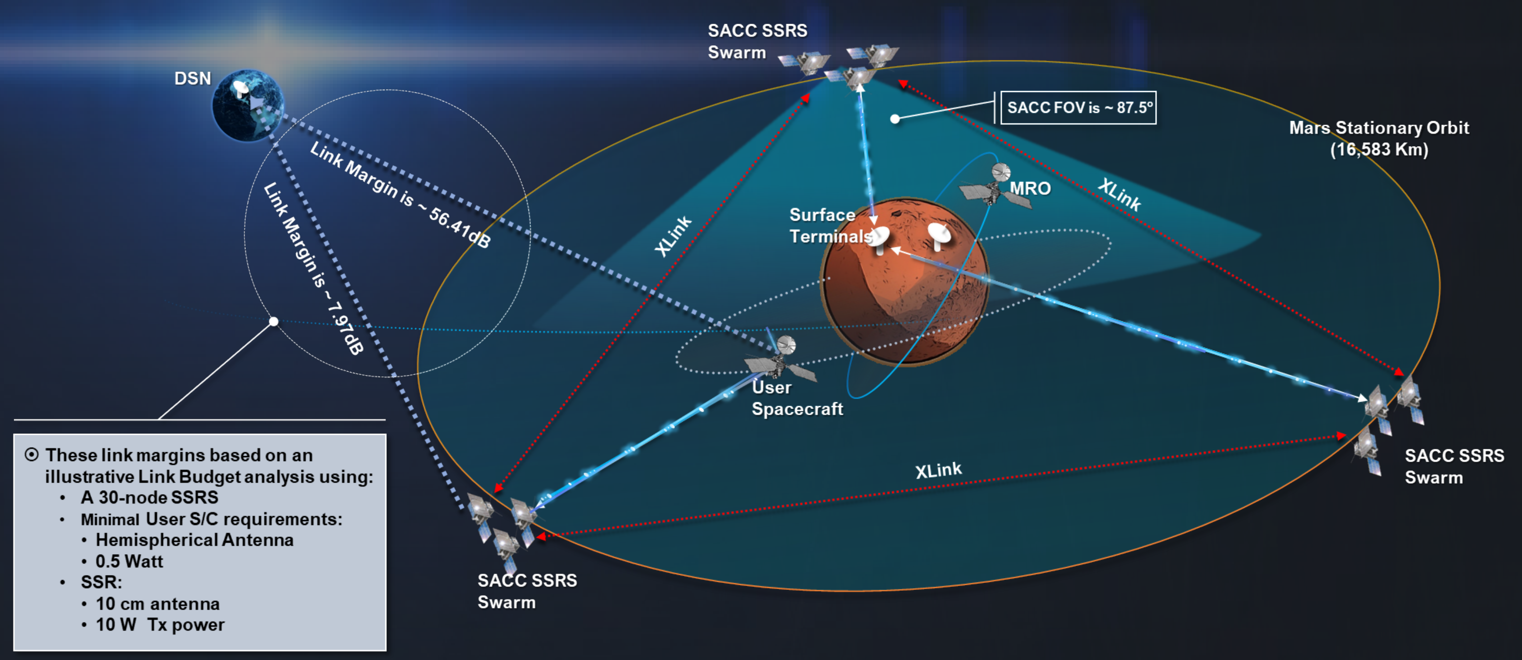
Illustrative Application (1): ‘Frozen’ Orbit SSRS Lunar Relay Constellation

- **Now, let’s investigate notional deployments of the SACC SSRS concept outside non-terrestrial orbits.**

  The first is for lunar operations using the Andromeda SmallSat constellation that has been proposed by Argotec and JPL. It uses a class of stable orbits known as ‘frozen’ orbits. Stable orbits make it easy to keep the satellites in their assigned orbits for the 5 years (or more) that they are expected to operate. The proposed orbits are elliptical, with a 12-hour period, a 57-degree inclination, and a distance to the moon’s surface from 720 kilometers at their closest points to 8,090 km at their farthest.

  The proposed Andromeda satellite constellation is composed of 24 satellites, each measuring just 44 by 40 by 37 centimeters when stored. These are divided evenly among four different orbits to provide maximum coverage for the moon’s surface. Each satellite in the proposed Andromeda constellation has three different antennas to establish communications with both Earth and the lunar surface.

  The application of SACC in this context would be to deploy SSRS swarms instead of single larger and more costly relay satellites to accommodate higher data rates and have the potential ability for wider FOVs and CDMA usage.



Illustrative Application (2): Mars SSRS Relay Constellation

- **The second notional deployment is a relay satellite system around Mars.**

It is fashioned after the TDRSS Relay concept. As with TDRSS, there are three 'stationary' orbital locations of swarms separated by 120° to provide 24x7 coverage of Mars surface and orbiter users. The Mars Stationary orbit altitude is lower at 16,583 km. In the Mars context, there are communications requirements for low orbiters, as well as significant surface-to surface and surface-to-orbit connectivity. The three SSRS constellations, along with their Xlinks, effectively act as 'cell towers' that can support comms across the entire Martian user regime with 24x7 service. The SSRSs also act as gateways back to earth.

As shown, there is a about a 64 dB link advantage for such a relay when deploying SSRS, which is primarily due the differential pathloss factor between going 401,000,000 km to earth at Ka-Band vs 20,000 km to the SRSS at S-band.

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**Patent Pending*