GALILEO
Station Keeping Strategy

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- **Walker 27/3/1 with 3 spare S/C per plane**
  - Planes RAAN separated by 120 degrees (initial RAAN still TBD)
  - 40 degrees between adjacent S/C in same plane
  - 13.33 degrees between closest S/C in adjacent planes

- **Inclination = 56 degrees**

- **Mean SMA = 29600 km**
  - 17 rev per 10 sidereal day
  - No resonance effect due to Earth Geo-potential

- **RAAN regression ~ 9.45 deg/year**
• Across track orbit keeping:
  ➢ RAAN variations < +/- 2°
  ➢ Inclination variations < +/- 2°
• Along track orbit keeping:
  ➢ Relative along track in the same orbit plane < +/- 3°
  ➢ Relative phasing variation between adjacent planes < +/- 3°
• Each of these requirements allows for degradations in DOP about 2% to 5%
• Combined violations degrades DOP by 14%
• Number of SK manoeuvres:
  ➢ One orbit keeping manoeuvre maximum per satellite life-time (12 years)
SIMULATION

• The results shown in this presentation are based on
  ➢ Start of simulations 21 March 2009, 00:00:00
  ➢ RAAN = 0, 120, 240 degrees
  ➢ S/C
    ✓ A1
    ✓ A2
    ✓ A9
    ✓ B1
    ✓ C9

• Disclaimer: The actual values of RAAN for a particular Epoch are not yet fixed.
• Mostly affected by Third-Body Perturbation
  ➢ Inclination drift depends on RAAN
  ➢ Each plane has a different inclination drift.
  ➢ Inclination excursions

• Correction by SK ΔV is expensive: 63 m/s per deg
• Launch Vehicle injection target is offset as to make inclination drift within tolerance

<table>
<thead>
<tr>
<th>Plane</th>
<th>Inclination (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>57.55</td>
</tr>
<tr>
<td>B</td>
<td>54.80</td>
</tr>
<tr>
<td>C</td>
<td>55.30</td>
</tr>
</tbody>
</table>
• Node regression due to $J_2$ is a function of inclination

\[
\dot{\Omega}_{J2} = -\frac{3}{2} J_2 \frac{\mu}{a^3} \left( \frac{R_{\oplus}}{a(1-e^2)} \right)^2 \cos i
\]

• Since the inclination drifts differently for each plane
Node regression is different for each plane

• Correction by SK $\Delta V$
is expensive: 53 m/s per deg
Solution: An iterative process computes the initial offsets of the RAANs and the offsets of the orbital inclination.

### Table 1: Initial RAAN & Inclination Offsets

<table>
<thead>
<tr>
<th>Plane</th>
<th>Inclination (deg)</th>
<th>RAAN (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>57.56</td>
<td>359.22</td>
</tr>
<tr>
<td>B</td>
<td>54.79</td>
<td>120.78</td>
</tr>
<tr>
<td>C</td>
<td>55.30</td>
<td>240.62</td>
</tr>
</tbody>
</table>
• Orbit phase \((\varphi) = \text{argument of latitude} (\omega + \nu)\)
  
  \[
  \frac{d\varphi}{dt} \bigg|_{J_2} = \sqrt{\frac{\mu}{a^3}} \left[ 1 + \frac{3}{2} J_2 \left( \frac{R_\oplus}{a} \right)^2 (4 \cos^2 i - 1) \right]
  \]
  
  \(e \approx 0\)

• Variations in inclination introduces up to half a second difference in the orbital period \(\rightarrow 2\) degrees de-phase in one year
  
  \(\Rightarrow\) Inclination initial value and evolution is “fixed” once Launch Vehicle target has been defined
  
  \(\Rightarrow\) Only degree of freedom is SMA

• All S/C in same plane have same inclination variation
  
  \(\Rightarrow\) Selecting same mean SMA, all S/C maintain phase difference

• S/C in different planes have different inclination variations
• Behaviour is similar in the other planes
• No manoeuvres needed
• Seems like good news… ??
ALONG-TRACK DIFFERENCE IN ADJACENT PLANES

- Different Phase drift behaviour in each plane
- Phase difference cannot be maintained within tolerance, not even
- Manoeuvres are needed
ALONG-TRACK DIFFERENCE IN ADJACENT PLANES

- "Minimizing" phase difference requires solving for three SMA values and three initial phase values
- Quite a complicated problem
- Does not guarantee that manoeuvres will not be needed
• Relative SK minimizes manoeuvre frequency… but not all the constellation tolerance requirements are define as relative:
  - Inclination maintenance is absolute by requirement
  - RAAN (for first plane) is a degree of freedom
    ✓ Once selected one value, the others follow up
    ✓ Minimize number of manoeuvres

• Phase difference requirements are relative…
  - Easy phase maintenance within each plane
    ✓ Use same mean SMA (and initial Inclination, of course)
  - Difficult phase maintenance among planes
    ✓ Phase Drift is different on each plane

• Absolute Station Keeping allows to handle satellites individually
• **REFERENCE CONSTELLATION**
  - Needs to reproduce the expected constellation geometry
    - Average Altitude = 23222 km (Constant) 17 rev / 10 sidereal days
    - Inclination = 56 degrees (Constant)
    - RAAN regression = 9.45 deg/year (Constant)
  - Dynamic model
    - Central Body
    - $J_2$
  - At Epoch 21 March 2009, 00:00:00
    - Phase $A_i = 40*(i-1)$ degrees
    - Phase $B_i = 13.33 + 40*(i-1)$ degrees
    - Phase $C_i = 26.66 + 40*(i-1)$ degrees
    - These phase values define the centre of the boxes
• **Tolerances**
  - Inclination and RAAN
    - 2 degrees as originally requested
    - Initial offset by Launch Vehicle injection target is enough
  - Phase difference in same plane
    - +/- 1.5 degrees
  - Phase difference between adjacent planes
    - +/- 1.5 degrees
• **Fulfilling these tolerances guarantees that the original requirements are met**
For each S/C, a particular SMA is applied to counterbalance the effect of inclination on the phase drift.

Simulations show that phase cannot be constrained to 3 degrees for longer than about 7 years for plane A and B.
• SMA optimized to maintain the phase variation within 3 degrees for 7 years
  ➢ Notice plane C behaviour
Along-track differences in same plane and between adjacent planes are maintained within original tolerances (as expected).
We can choose RAAN so that at least one plane does not need manoeuvres.

\[ \frac{d^2 \varphi}{dt^2} < 0 \]

\[ \frac{d^2 \varphi}{dt^2} > 0 \]
• Error in SRP ➢ +/- 10%
• Error in SMA ➢ +/- 5 metres
• Some margin is needed to account for these errors
• **ABSOLUTE STATION KEEPING**

  ➢ Understanding of the problem dynamics
  ➢ Reference Constellation
    ✓ S/C position is well determined
  ➢ Satellites are handled individually
  ➢ Inclination and RAAN are achieved by Launch Vehicle Injection
    ✓ Savings in S/C propellant
    ✓ Inclination targeting complicates launch program
  ➢ Along-track is maintained with respect reference constellation
    ✓ Simplifies SK and guarantees tolerances
    ✓ Fine-positioning after LEOP
    ✓ SK manoeuvre about 7 years later
    ✓ RAAN can be selected so one plane does not need SK manoeuvre
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