TSP-2 Software to Point SAR Targets

Yaraskavitch, Marshall, Hawkins,

Gibson, Crocker
Some Context
Geohazard Site Locations

- Thunder River
- Buckinghorse
- Little Smokey
- Ottawa
Geo-Hazards In-SAR Study
RS-1 Imagery Little Smokey
Thunder River Site
Purpose in Developing TSP

Determine Azimuth & Elevation pointings for RS-2

- Arbitrary location on earth
- Initially for RS-2 transponder
- Extended to other satellites:
  - RS-1, ENVISAT, TerraSAR-X, ALOS, COSMO-SkyMed
- Extended for CRs and other targets
- General need for user community
Yaw-Steered Pointing – RS-2

\[
\frac{d\phi}{dt} = \frac{d}{dt} \left( \frac{4\pi R}{\lambda} \right) = 0
\]

\[
\frac{d}{dt} \left( \vec{P}_s(t) - \vec{P}_o \right) = \frac{dR}{dt} = 0
\]

- Requires Target location
- Requires Satellite location
\[
\mathbf{R}(t) \cdot \mathbf{v}(t) = 0
\]

\[
\left( \mathbf{P}_s(t) - \mathbf{P}_o \right) \cdot \frac{d\mathbf{P}_s(t)}{dt} = 0
\]

- Require Target location
- Require Satellite location
- Require Satellite velocity
Finding Satellite Position

- How do we implement this? –Use NORAD TLEs
  - Freely available
  - Standard for Orbit description
  - Well established propagators available for development
- SGP-4 (Simplified General Perturbations) Propagator
  - Position, velocity wrt time from TLEs
  - Existing MATLAB® code
- Other issues
  - Coordinate frames
  -Calculating Pointings
Pointing Requirements

- **Angular Resolution**
  - $\Delta \theta = \pm 0.01^\circ$ for azimuth and elevation
  - For a target $R=1000$ km, $\Delta s = \pm 170$ m

- **Time Resolution**
  - Not crucial for ‘event’ time
    - few seconds
  - Crucial for orbit propagation.
    - $v \sim 7.5$ km/s for RS-1
    - Can therefore travel 0.17 km in ~0.02 s
Coordinate Transforms

- **Propagator output:**
  - True Equator Mean Equinox (TEME) frame
  - X axis in direction of vernal equinox, Z axis of rotation

- **Optimal satellite position calculation:**
  - Earth Centred, Earth Fixed (ECEF)
    - X axis points towards \((0°,0°)\), Z axis of rotation
  - Local vertical (ENU) (East, North, Up) \(\Rightarrow\) (X,Y,Z)

- **Azimuth and Elevation Calculation:**
  - Local Polar Coordinates (LPC) (Az, El, Range)
Coordinate Transforms

True Equator Mean Equinox (TEME)

\[ \vec{r}_{PEF} = \begin{bmatrix} \cos(-\theta_{GMST}) & \sin(-\theta_{GMST}) & 0 \\ -\sin(-\theta_{GMST}) & \cos(-\theta_{GMST}) & 0 \\ 0 & 0 & 1 \end{bmatrix} \vec{r}_{TEME} \]

\[ \vec{v}_{PEF} = \begin{bmatrix} \cos(-\theta_{GMST}) & \sin(-\theta_{GMST}) & 0 \\ -\sin(-\theta_{GMST}) & \cos(-\theta_{GMST}) & 0 \\ 0 & 0 & 1 \end{bmatrix} \vec{v}_{TEME} - \alpha (\vec{\omega}_{Earth} \times \vec{r}_{PEF}) \]

Neglecting polar wobble

Earth Centred Earth Fixed (ECEF)

\[ \vec{r}_{satellite\_ENU} = \begin{bmatrix} -\sin \phi & \cos \phi & 0 \\ -\cos \phi \sin \lambda & -\sin \phi \sin \lambda & \cos \lambda \\ \cos \phi \cos \lambda & \cos \lambda \sin \phi & \sin \lambda \end{bmatrix} \vec{r}_{satellite\_ECEF} - \vec{r}_{observer\_ECEF} \]

\[ \vec{v}_{satellite\_ENU} = \begin{bmatrix} -\sin \phi & \cos \phi & 0 \\ -\cos \phi \sin \lambda & -\sin \phi \sin \lambda & \cos \lambda \\ \cos \phi \cos \lambda & \cos \lambda \sin \phi & \sin \lambda \end{bmatrix} \vec{v}_{satellite\_ECEF} \]

Local Vertical, East-North-Up (ENU)

\[ range = |\vec{r}_{ENU}| \]

\[ azimuth = \arctan \left( \frac{y_{ENU}}{x_{ENU}} \right) \]

\[ elevation = \arctan \left( \frac{z_{ENU}}{\sqrt{x_{ENU}^2 + y_{ENU}^2}} \right) \]

Range, Azimuth, and Elevation (LPC)
- SW written in MATLAB®, two primary modes:
  - **Fast**
    - Inputs: satellite, target location, and approximate event time
    - Orbit found from TLE archive
    - Outputs: Optimal pointing
  - **Custom**
    - Inputs: satellite, target location, time window, initial time step, specific TLE, and polar wobble coordinates
    - Orbit found from specific TLE
    - Outputs: Optimal pointing
  - **Batch**
    - Table input/output
Opening Screen

TSP-2: Mode Selection

Which input mode would you like?

- Fast
- Custom
- Generate new TLE
- Update using NORAD TLE sets from Celestrak.com
- Review TLE
- Magnetic Declination
- Help
TPS-2: Satellite Selection

Select Constellation or

RADARSAT
Cosmo-SkyMed
ALOS
ENVIROSAT
ERS-2
TERRASAR-X
Custom

Specify Satellite within constellation

Selected
RS1
RS2

Next

Back
Help
Target Location Selection – Canned or Custom

TPS-2: Target Location Query

Observer Location

Cottages
Resolute
Fredericton
Prince Albert
Custom LLA
Custom Definition File

Next

Back
Help
TPS-2: Event Time Query

Please enter the date and time of event:

Day  Month  Year  Hour  Minute  Second
16     11     2009   2      43      30  Next

Help Dialog

Please enter the desired time(UTC) for event. TSP will search in a timeframe around this event to find the optimal time and pointings.
Geometrical Confirmation

Target Location

Nadir Point

Satellite: RADARSAT1
Pass: Descending
Right Looking

UTC Time: 23-Jan-2009 11:10:24
Local Time (At Target): 23-Jan-2009 06:10:24
Time Zone: UTC-6 America/Toronto

Azimuth: 97.9443°
Elevation: 55.0179°

Deselct all tools, and click an arrow head -
Time from initial position (mins): 3
UTC time: 23-Jan-2009 11:13:24
Local Time(According to observer lat/long): 23-Jan-2009 06:13:24
Latitude (deg): 35.7
Longitude (deg) -72.6
Height (km): 796.1
Azimuth: 165.0
Elevation: 29.5
Field Geometry

3D View

Overhead View

\( \phi_N = 46.00^\circ \)

\( \theta_{az} = 136.00^\circ \)

Side View

North
Example Textual Dump

**TSP 2.0: Target-to-Satellite Pointings**

Epoch time of TLE used for nominal orbit: 2008 7 9 13: 9:36.067378

ECF records written to test.out, first table entry @ TLE epoch

**Optical Setting:**
Minimum distance from satellite to observer (km): 1006.3769
Minimum result record number: 29

**Time (UTC):** 2008/7/9 22:58:55.746972
**Time from Epoch (min):** -10.67
X(km): 634.338 Y(km): -5114.702 Z(km): 4977.960
Vx (km/s): -2.335 Vy(km/s): 4.800 Vz(km/s): 5.242

**Corresponding date:** 06-Mar-2009 22:58:55
**Observer Azimuth (degrees):** 134.1385
**Observer Elevation (degrees):** 49.7105
**Corner reflector elevation from base (degrees):** 14.4461

**Satellite latitude:** 49.1707
**Satellite longitude:** -92.3074
**Satellite altitude (km):** 797.7679

**Angle between satellite and observer vector:** 8.1104
**Angle between satellite and range vector:** 38.0466
**Angle between observer and range vector:** 139.7411
**Magnitude of Satellite Position Vector (km):** 7163.5614
**Magnitude of Satellite Velocity Vector (km):** 7.5461

**Beam Velocity (km/s):** 6.6782

Unit vector from Target to Satellite: X(m): -0.4461 Y(m): -0.72 Z(m): 0.4442

Pointings saved to pointing.out
RS-1 vs TSP Results

- Ottawa RPT Events 2007/08 to 2008/06
  - RMS errors:
    - Azimuth 0.06°
    - Elevation 0.03°
ENVISAT vs TSP Results

- Res RPT Events 2005/07 to 2005/08
  - RMS errors:
    - Azimuth 0.11°
    - Elevation 0.04°
Conclusions

- A general new tool, **TSP-2**, has been developed and validated for Target Pointing.
- Currently being used for Validation of RS-2
- Government and Commercial Clients
- Available through CCRS
- Hire a Student or Two!
**Orbit Accuracy Testing**

- **Historical RS-1 and ENVISAT RPT pointings**
  - RPT pointings empirically correct to ~0.1°

- **Compare TSP to STK results**
  - **Premise**: STK is industry standard propagator
  - STK allows TLE input
### Pointing Error - TSP vs STK

- Pointings for events between 2008/07/02, 00:00:00 to 12:00:00
- Same TLE’s used

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Location</th>
<th>Δ Azimuth (°)</th>
<th>Δ Elevation (°)</th>
<th>Δ Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS2</td>
<td>ON0</td>
<td>0.001</td>
<td>0.001</td>
<td>-22.16</td>
</tr>
<tr>
<td>RS1</td>
<td>ON0</td>
<td>-0.001</td>
<td>-0.001</td>
<td>-9.94</td>
</tr>
<tr>
<td>ENVISAT</td>
<td>ON0</td>
<td>-0.001</td>
<td>0.000</td>
<td>-20.62</td>
</tr>
<tr>
<td>TERRASAR-X</td>
<td>ON0</td>
<td>0.000</td>
<td>-0.001</td>
<td>-5.51</td>
</tr>
<tr>
<td>ALOS</td>
<td>ON0</td>
<td>0.002</td>
<td>0.000</td>
<td>-20.46</td>
</tr>
<tr>
<td>RS2</td>
<td>NT0</td>
<td>-0.011</td>
<td>-0.001</td>
<td>-0.42</td>
</tr>
<tr>
<td>RS1</td>
<td>NT0</td>
<td>-0.001</td>
<td>0.000</td>
<td>-13.79</td>
</tr>
<tr>
<td>ENVISAT</td>
<td>NT0</td>
<td>0.001</td>
<td>-0.001</td>
<td>-17.74</td>
</tr>
<tr>
<td>TERRASAR-X</td>
<td>NT0</td>
<td>0.001</td>
<td>-0.001</td>
<td>-11.83</td>
</tr>
<tr>
<td>ALOS</td>
<td>NT0</td>
<td>-0.004</td>
<td>0.000</td>
<td>-18.48</td>
</tr>
<tr>
<td><strong>RMS Average</strong></td>
<td></td>
<td><strong>0.004</strong></td>
<td><strong>0.001</strong></td>
<td><strong>15.66</strong></td>
</tr>
</tbody>
</table>
### Absolute Position Error – TSP vs STK

#### Difference in ECEF position

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Location</th>
<th>Δ X (m)</th>
<th>Δ Y (m)</th>
<th>Δ Z (m)</th>
<th>Δ R (m)</th>
<th>Relative Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS2</td>
<td>ON0</td>
<td>7.06</td>
<td>-23.22</td>
<td>-6.72</td>
<td>25.18</td>
<td>0.0004%</td>
</tr>
<tr>
<td>RS1</td>
<td>ON0</td>
<td>7.99</td>
<td>-11.87</td>
<td>2.30</td>
<td>14.49</td>
<td>0.0002%</td>
</tr>
<tr>
<td>ENVISAT</td>
<td>ON0</td>
<td>-2.77</td>
<td>2.89</td>
<td>20.56</td>
<td>20.95</td>
<td>0.0003%</td>
</tr>
<tr>
<td>TERRASAR-X</td>
<td>ON0</td>
<td>9.66</td>
<td>-25.84</td>
<td>-11.33</td>
<td>29.82</td>
<td>0.0004%</td>
</tr>
<tr>
<td>ALOS</td>
<td>ON0</td>
<td>-4.03</td>
<td>-3.40</td>
<td>15.31</td>
<td>16.20</td>
<td>0.0002%</td>
</tr>
<tr>
<td>RS2</td>
<td>NT0</td>
<td>-1.36</td>
<td>199.65</td>
<td>70.35</td>
<td>211.69</td>
<td>0.0030%</td>
</tr>
<tr>
<td>RS1</td>
<td>NT0</td>
<td>6.54</td>
<td>16.45</td>
<td>23.34</td>
<td>29.29</td>
<td>0.0004%</td>
</tr>
<tr>
<td>ENVISAT</td>
<td>NT0</td>
<td>-9.03</td>
<td>22.51</td>
<td>23.73</td>
<td>33.93</td>
<td>0.0005%</td>
</tr>
<tr>
<td>TERRASAR-X</td>
<td>NT0</td>
<td>15.94</td>
<td>37.83</td>
<td>29.97</td>
<td>50.83</td>
<td>0.0007%</td>
</tr>
<tr>
<td>ALOS</td>
<td>NT0</td>
<td>-8.14</td>
<td>7.74</td>
<td>19.75</td>
<td>22.72</td>
<td>0.0003%</td>
</tr>
<tr>
<td><strong>RMS Average</strong></td>
<td></td>
<td>8.23</td>
<td>65.95</td>
<td>28.60</td>
<td>72.36</td>
<td>0.0010%</td>
</tr>
</tbody>
</table>
### Along/Across Track Error – TSP vs STK

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Location</th>
<th>Along track error ( \hat{v} \cdot \Delta r ) (m)</th>
<th>Radial error ( \hat{r} \cdot \Delta r ) (m)</th>
<th>Across track error ( \hat{v} \times \hat{r} \cdot \Delta r ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS2</td>
<td>ON0</td>
<td>20.82</td>
<td>12.26</td>
<td>7.15</td>
</tr>
<tr>
<td>RS1</td>
<td>ON0</td>
<td>7.28</td>
<td>11.83</td>
<td>4.15</td>
</tr>
<tr>
<td>ENVISAT</td>
<td>ON0</td>
<td>16.99</td>
<td>12.02</td>
<td>-2.25</td>
</tr>
<tr>
<td>TERRASAR-X</td>
<td>ON0</td>
<td>27.07</td>
<td>11.98</td>
<td>3.71</td>
</tr>
<tr>
<td>ALOS</td>
<td>ON0</td>
<td>10.15</td>
<td>12.37</td>
<td>2.42</td>
</tr>
<tr>
<td>RS2</td>
<td>NT0</td>
<td>-210.90</td>
<td>16.86</td>
<td>6.65</td>
</tr>
<tr>
<td>RS1</td>
<td>NT0</td>
<td>22.44</td>
<td>16.95</td>
<td>-8.16</td>
</tr>
<tr>
<td>ENVISAT</td>
<td>NT0</td>
<td>29.23</td>
<td>17.08</td>
<td>-2.11</td>
</tr>
<tr>
<td>TERRASAR-X</td>
<td>NT0</td>
<td>46.79</td>
<td>17.08</td>
<td>-10.06</td>
</tr>
<tr>
<td>ALOS</td>
<td>NT0</td>
<td>14.79</td>
<td>17.20</td>
<td>1.14</td>
</tr>
<tr>
<td>RMS Average</td>
<td></td>
<td><strong>70.61</strong></td>
<td><strong>14.77</strong></td>
<td><strong>5.57</strong></td>
</tr>
</tbody>
</table>

- Majority of error in along-track direction (i.e. direction of velocity)
- Very small error in across-track direction
A Versatile Tools is available for Growing Community

- > $4M in CRs by one Cdn Company in 2008
- InSAR – Geohazards
  - Subsidence
  - Landslides
  - Plate shifting
- Phase Calibration
- Amplitude Calibration
- Positioning
Reflector Installation Above Permafrost
References


Keplerian Elements:
- Semi-major axis of orbit
- Eccentricity of orbit
- Mean motion
- Inclination
- Right ascension of ascending node
- Argument of perigee
- True anomaly
- Mean motion dot
- Mean motion dot dot
- Bstar drag parameter