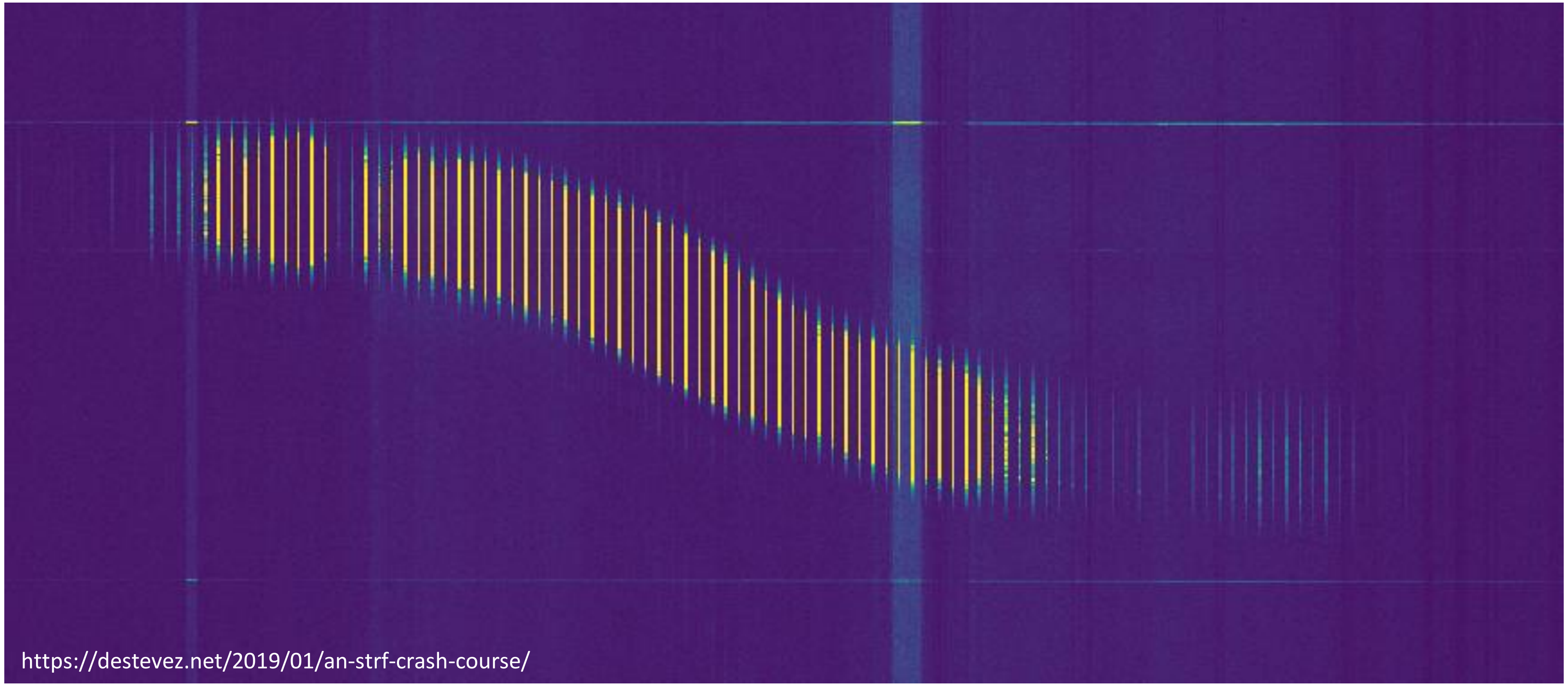


Doppler Based Orbit Determination with Optimization

Open Source CubeSat Workshop 2020

Mehmet Fatih ERTÜRK

In collaboration with: Arabacı, M.C., Cirtil, H.M., Erdenk, B., Ertürk, M.F., Ghanbarpourasl, H., Kaya, M., Sisman, T.C. and Yenidoğan, K.

Arabacı, M.C., Cirtil, H.M., Erdenk, B., Ertürk, M.F., Ghanbarpourasl, H., Kaya, M., Sisman, T.C. and Yenidoğan, K.(2020), *Doppler Ölçümlerinin Optimizasyonla Yörünge Tespitinde Kullanılması (Orbit Determination with Doppler Measurements Using Optimization)*, VIII. Ulusal Havacılık ve Uzay Konferansı (8th National Aerospace Conference), Ankara, Turkey, Sept 2020.
UHUK-2020-154

- Introduction
  - Obtaining Data for the Orbit Determination Methods
  - Doppler Based Orbit Determination
- Method
  - Doppler Shift
  - Generating Artificial Data
  - Optimization
  - Differential Correction
- Results for Artificial and Real Data

How to Get Data for Orbit Determination?

Optic Based

-Optic observations
-Lidar (Light Detection and Ranging)

NROL-76 Visible Pass of a Spy Satellite
http://langbroek.org/

Radio Based

-Doppler
-Radar (Radio Detection and Ranging)

Kiwi Space Radar, New Zeland
https://www.leolabs.space/

How to Get Data for Orbit Determination?

Optic Based

-Optic observations

-Lidar (Light Detection and Ranging)

- SeeSat-L
- TruSat

Radio Based

-Doppler

-Radar (Radio Detection and Ranging)

SatNOGS

#510 – UTAA Astro TEST

Antennas

- UHF-VHF Cross Yagi
- UHF Yagi
- VHF Yagi
- VHF Turnstile
- L-band

Doppler Based Orbit Determination

Guier, McClure and Weiffenbach

https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/transit

Gavaghan, H., Something New Under the Sun: Satellites and the Beginning of the Space Age, Copernicus (1998)

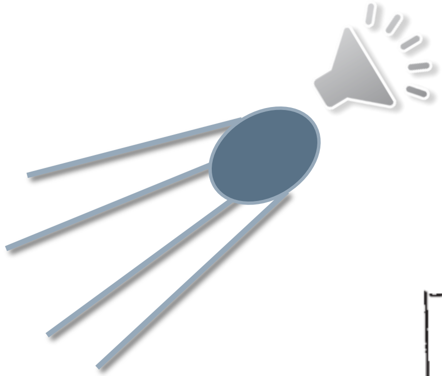


Table 1. SPUTNIK I: 20 Mc./s.

Estimated experimental error	± 4 c./s.
Root-mean-square fit to observations	± 1·6 c./s.
Approximate ground-range	73 stat. miles
Minimum angle of arrival from horizon	20°
t_0 = 2347 G.C.T., October 21, 1957	
Latitude of *O*	38° 41′ N.
Longitude of *O*	75° 59′ W.

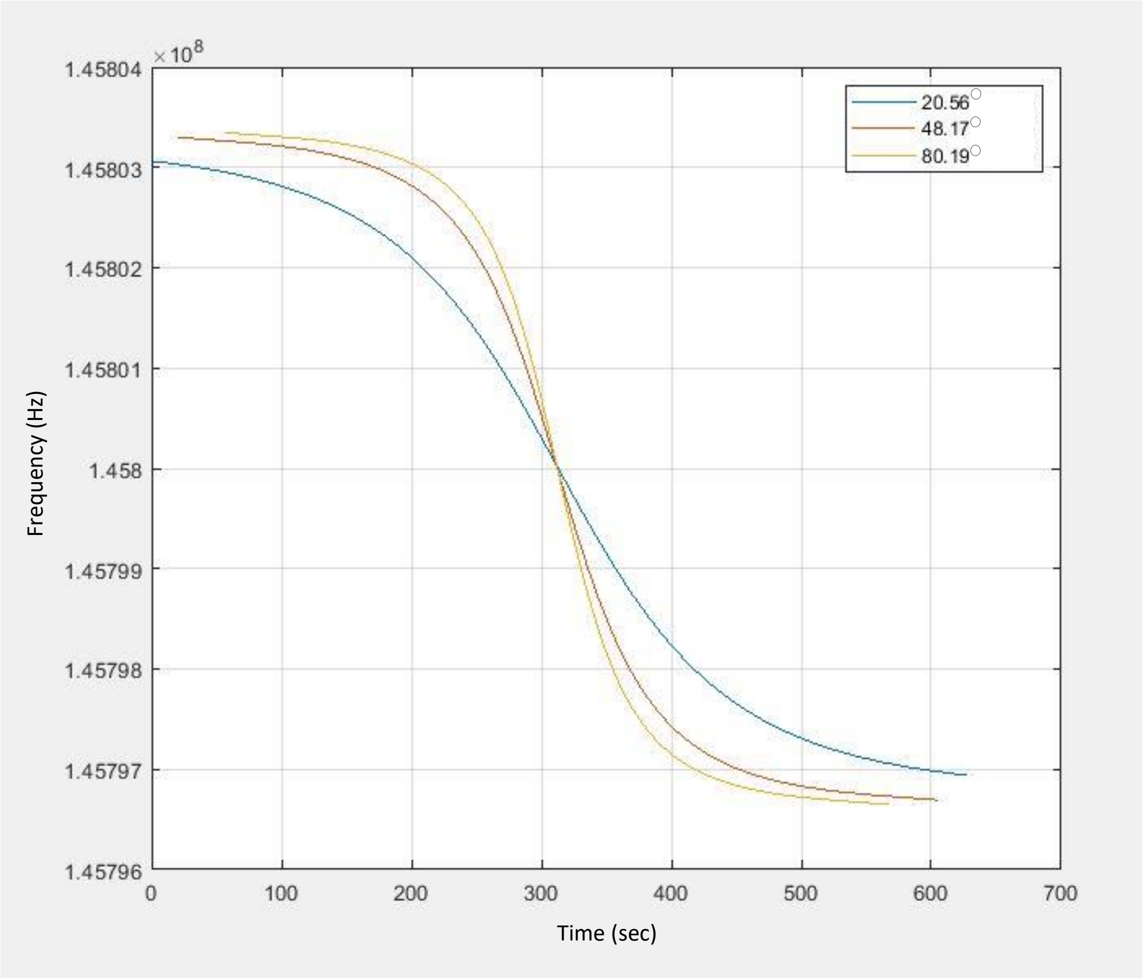
Orbit element	Doppler determination	Ref. 1*	Ref. 2†
Period	95 min. 38 sec.	95 min. 36 sec.	95 min. 34 sec.
Eccentricity	0·053	0·053 ± 0·001	0·048 ± 0·002
Inclination	64° 10′	64° 40′ ± 10′	65°
Arg. of perigee	43° 30′	—	—
Latitude of perigee	38° 20′ N.	36° ± 3° N.	40·9° N.
Longitude of asc. node	289°	291·6° ± 0·3°	—

* Staff of the Mullard Radio Astronomy Observatory, Cambridge, *Nature*, 180, 879 (1957).
† Staff of the Royal Aircraft Establishment, Farnborough, *Nature*, 180, 937 (1957).

Guier, W.H. ve Weiffenbach, G.C. (1958)

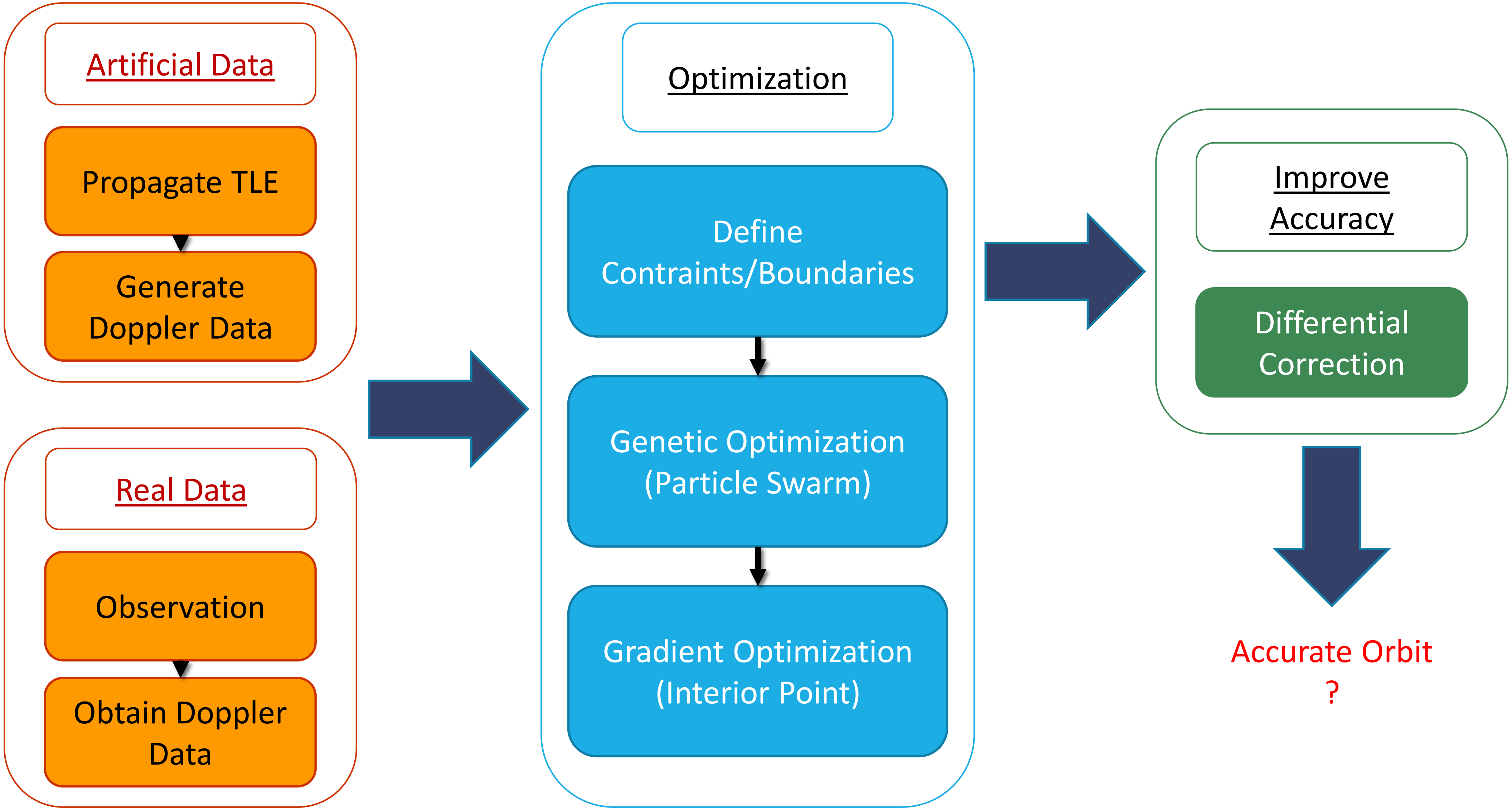
https://soundcloud.com/nasa/sputnik-beep

Doppler Shift



The Effect of Maximum Elevation Angle to Doppler Shift

Path of the Study



Generating Artificial Data

TLE → Two Body Propagator → $\dot{\rho}(t) = \vec{v} \cdot \left(\frac{\vec{\rho}}{\rho}\right)$

Two Body Propagator

- To simplify calculations
- To reduce computation time

$$\dot{\rho}(t) = \vec{v} \cdot \left(\frac{\vec{\rho}}{\rho}\right)$$

Boundaries and Constraints

Low Earth Orbit
Altitude: ~200-2000 km

- **Circular Orbit**

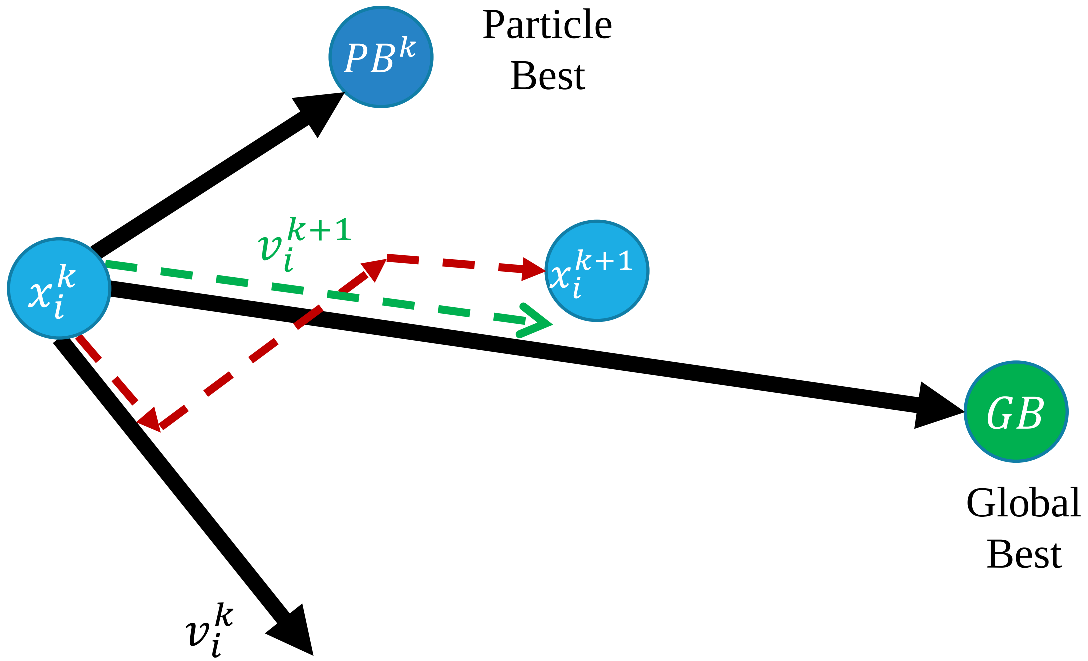
  $a_{min} = 6500$ km
  $a_{max} = 8500$ km
  $e = 0$

- **Elliptic Orbit**

  $a_{min} \sim 6500$ km
  $a_{max} \sim 8500$ km
  $r_{p\_min} \sim 6500$ km
  $r_{a\_max} \sim 8500$ km
  $e_{min} = 0$
  $e_{max} \sim 0.133$

- $i_{prograde} = [0°, 90°]$, $i_{retropgrade} = [90°, 180°]$
- $\Omega, \omega, \theta = [0°, 360°]$

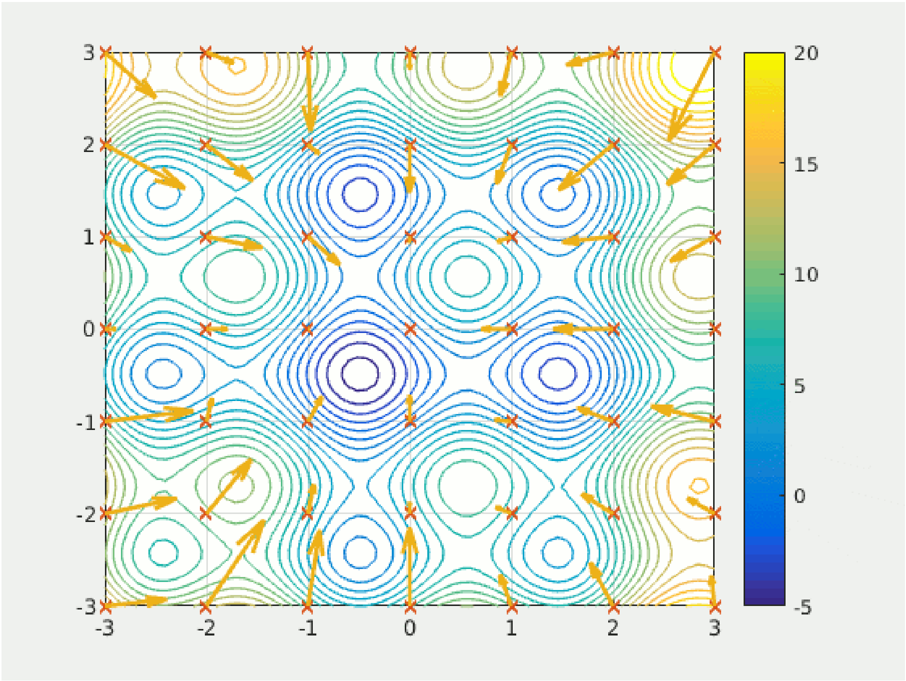
Particle Swarm Optimization (PSO)



$$v_i^{k+1} = wv_i^k + r_1c_1\left(PB^k - x_i^k\right) + r_2c_2\left(GB - x_i^k\right)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1}$$

Clerc, M. ve Kennedy, J. (2002)



Search of a Swarm for Optimum Point
https://en.wikipedia.org/wiki/Particle_swarm_optimization

Find: Minimum RMS $= \sqrt{\frac{(\dot{\rho}_{observed} - \dot{\rho}_{calculated})^2}{Number\ of\ Data}}$

Differential Correction

ALGORITHM 67: Differential Correction (*Obs at* t_i, $\hat{X}_{nom} \Rightarrow \hat{X}_o$)

FOR $i = 1$ to the number of observations N

Propagate the nominal state to each t_i and find computed observations

$$\hat{X}_{nom_i} = \int_{t_o}^{t} \dot{\hat{X}}_{nom}\, dt + \hat{X}_{nom}$$

RAZEL ($\vec{r}_{nomECI}$, $\vec{v}_{nomECI}$, *yr, mo, day, UTC,*

$\Delta UT1, \Delta AT, x_p, y_p, \phi_{gd}, \lambda, h_{ellp} \Rightarrow \rho, \beta, el, \dot{\rho}, \dot{\beta}, \dot{el}$)

Find the $\tilde{b}$ matrix as observed minus computed data at each t_i

Perform Finite Differencing for the A matrix, or:

$$\frac{d\hat{X}}{dt} = \dot{\hat{X}}_{2-body} + \dot{\hat{X}}_{nonspherical} + \dot{\hat{X}}_{drag} + \dot{\hat{X}}_{3-body} + \dot{\hat{X}}_{SR} + \dot{\hat{X}}_{other}$$

$$F = \frac{\partial \dot{\hat{X}}}{\partial \hat{X}} \qquad \Phi(t, t_o) = \int_{t_o}^{t} F(t)\Phi(t, t_o)\, dt$$

$$A = \frac{\partial\, \text{observations}}{\partial \hat{X}} \frac{\partial \hat{X}}{\partial \hat{X}_o} = H\Phi$$

Accumulate $A^T W A$ and $A^T W \tilde{b}$

END LOOP

$$\delta\hat{x} = (A^T W A)^{-1} A^T W \tilde{b} = P A^T W \tilde{b}$$

$$\text{Check RMS for convergence} = \sqrt{\frac{\tilde{b}^T W \tilde{b}}{n_{meas}(N)}}$$

Update the state vector and repeat if not converged:

$$\hat{X}_{nom} = \hat{X}_{nom} + \delta\hat{x}$$

Vallado, D.A., Fundamentals of Astrodynamics and Applications, 4th Edition, Space Technology Library, (1997)

(1) $\vec{X}_{nominal} = [a_0 e_0 i_0\ \Omega_0\ \omega_0\ \theta_0]$

(2) $\tilde{\boldsymbol{b}} = \left[\dot{\boldsymbol{\rho}}_{observation_{(Nx1)}} - \dot{\boldsymbol{\rho}}_{calculated_{(Nx1)}}\right]$

(3) $\delta\vec{x} = \vec{X}_{nominal} * 0.01$

(4) $\boldsymbol{A} = \frac{\delta observation}{\delta \vec{X}_0} \approx \frac{f(\vec{X}_{nominal} + \delta\vec{x}) - f(\vec{X}_{nominal})}{\delta\vec{x}}$

(5) $\delta\vec{X} = (\boldsymbol{A}^T \boldsymbol{W} \boldsymbol{A})^{-1} \boldsymbol{A}^T \boldsymbol{W} \tilde{\boldsymbol{b}}$

(6) $\delta\vec{X} = (\boldsymbol{A}^T \boldsymbol{A})^{-1} \boldsymbol{A}^T \tilde{\boldsymbol{b}}$

(7) $\vec{X}_{nominal} = \vec{X}_{nominal} + \delta\vec{X}$

Results for Artificial Data

Obtained best Keplerian Elements during the genetic optimization for the ISS.

Data Types	$RMS\ (km/s)$	$a\ (km)$	e	$\Omega\ (°)$	$i\ (°)$	$\omega\ (°)$	$\theta\ (°)$	$\omega + \theta\ (°)$
Reference	0	6797.3239	0.0001128	91.0487	51.6401	7.3517	352.7633	0.1150
PSO	23.2622	6839.6043	0	113.9495	64.7159	128.4201	228.7715	357.1917
Absolute Error	23.2622	85.461	0.0001128	22.9008	13.0758	121.0684	123.9918	2.9233
Differential Correction	1.9076	6814.8966	0.002469	93.8964	52.7811	108.3800	254.2681	2.6481
Absolute Error	**1.9076**	**17.5727**	0.0023562	**2.8477**	**1.141**	101.0283	98.4952	**2.5331**

Accuracy

- ✓ $\Omega, i, (\omega + \theta) < 3°$
- ✓ $a < 20$ km

Results for Artificial Data

Obtained best Keplerian Elements during the gradient optimization for the ISS.

Artificial Data	$RMS\ (km/s)$	$a\ (km)$	e	$\Omega\ (°)$	$i\ (°)$	$\omega\ (°)$	$\theta\ (°)$	$\omega + \theta\ (°)$
Reference	0	6797.3239	0.0001128	91.0487	51.6401	7.3517	352.7633	0.1150
Gradient	0.0978	6796.4076	0	91.1522	51.6913	152.1694	207.6454	359.8148
Absolute Error	**0.0978**	**0.9163**	0.0001128	**0.1035**	**0.0512**	144.8177	145.1179	**0.3002**

Accuracy

- ✓ $\Omega, i, (\omega + \theta) < 1°$
- ✓ a <1 km

Results for Artificial Data

The comparison of the reference state vectors and the results of the gradient optimization for the ISS.

Artificial Data	$RMS\ (km/s)$	$r\ (km)$	$r_x\ (km)$	$r_y\ (km)$	$r_z\ (km)$	$v\ (km/s)$	$v_x\ (km/s)$	$v_y\ (km/s)$	$v_z\ (km/s)$
Reference	0	6797.3239	−132.8566	6795.2562	10.0967	7.6586	−4.7518	−0.1025	**6.0053**
Gradient	0.0978	6796.4076	−123.0483	6795.2718	−17.2382	7.6582	−4.7468	−0.0707	6.0093
Absolute Error	0.0978	**0.9163**	9.8083	0.0156	**27.3349**	**0.0004**	0.0050	0.0318	0.0040

Accuracy

- ✓ $r < 1$ km
- ✓ $v < 1$ m/s

Results for Artificial Data with Different Types of Orbit

Obtained best Keplerian Elements after the optimization process for different orbit types.

Eccentricity increases

	Data Types	$RMS\ (km/s)$	$a\ (km)$	e	$\Omega\ (°)$	$i\ (°)$	$\omega\ (°)$	$\theta\ (°)$	$\omega+\theta\ (°)$
ISS	**Reference**	0	**6797.3239**	0.0001128	91.0487	51.6401	7.3517	352.7633	**0.1150**
	The Best Result	0.0978	**6796.4076**	0	91.1522	51.6913	152.1694	207.6454	**359.8148**
NOAA-19	**Reference**	0	7229.2044	0.001298	**229.1645**	**99.1957**	288.9491	71.1680	**0.1171**
	The Best Result	$1.194x10^{-8}$	7235.7385	0	**229.0974**	**99.1796**	181.7058	179.4342	**0.0114**
Express MD2	**Reference**	0	**8518.0033**	**0.2206**	338.5851	49.8869	172.2323	187.8422	0.0745
	The Best Result	0.3587	**8519.4081**	**0.2240**	237.6580	57.2400	243.4523	188.0347	71.4870

✓ Increasing on the **ellipticity decreases accuracy**, but **eccentricity becomes predictible.**

Obtaining Real Data

Gurwin Techsat 1B - Satellite Information

Designation

Spacetrack catalog number	25397
COSPAR ID	1998-043-D
Name in Spacetrack catalog	TECHSAT 1B

Amateur radio information

Downlink: 435.225 MHz
Uplink: 145.850/145.930 MHz

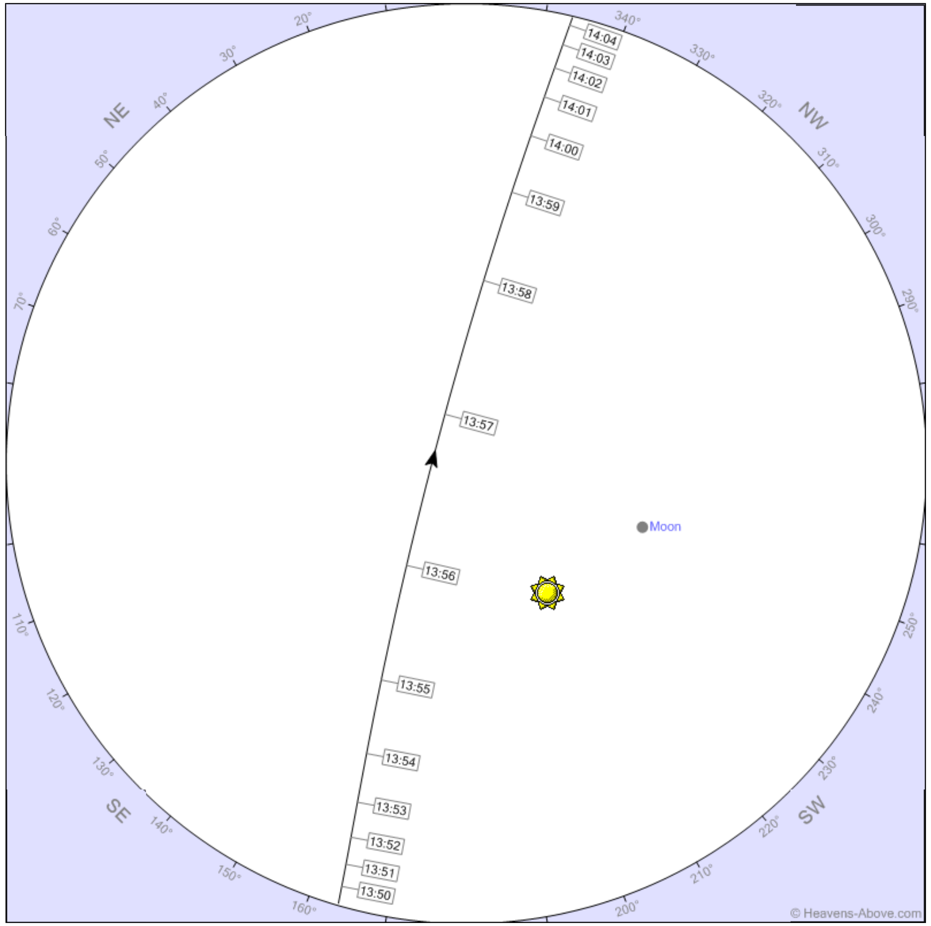
Satellite Details

Orbit	812 x 813 km, 98.7°
Category	unknown
Country/organisation of origin	Israel
Intrinsic brightness (Magnitude)	9.2 (at 1000km distance, 50% illuminated)
Maximum brightness (Magnitude)	8.3 (at perigee, 100% illuminated)

Launch

Date (UTC)	10 July 1998 06:30
Launch site	Baikonur Cosmodrome, Kazakhstan
Launch vehicle	Zenit-2

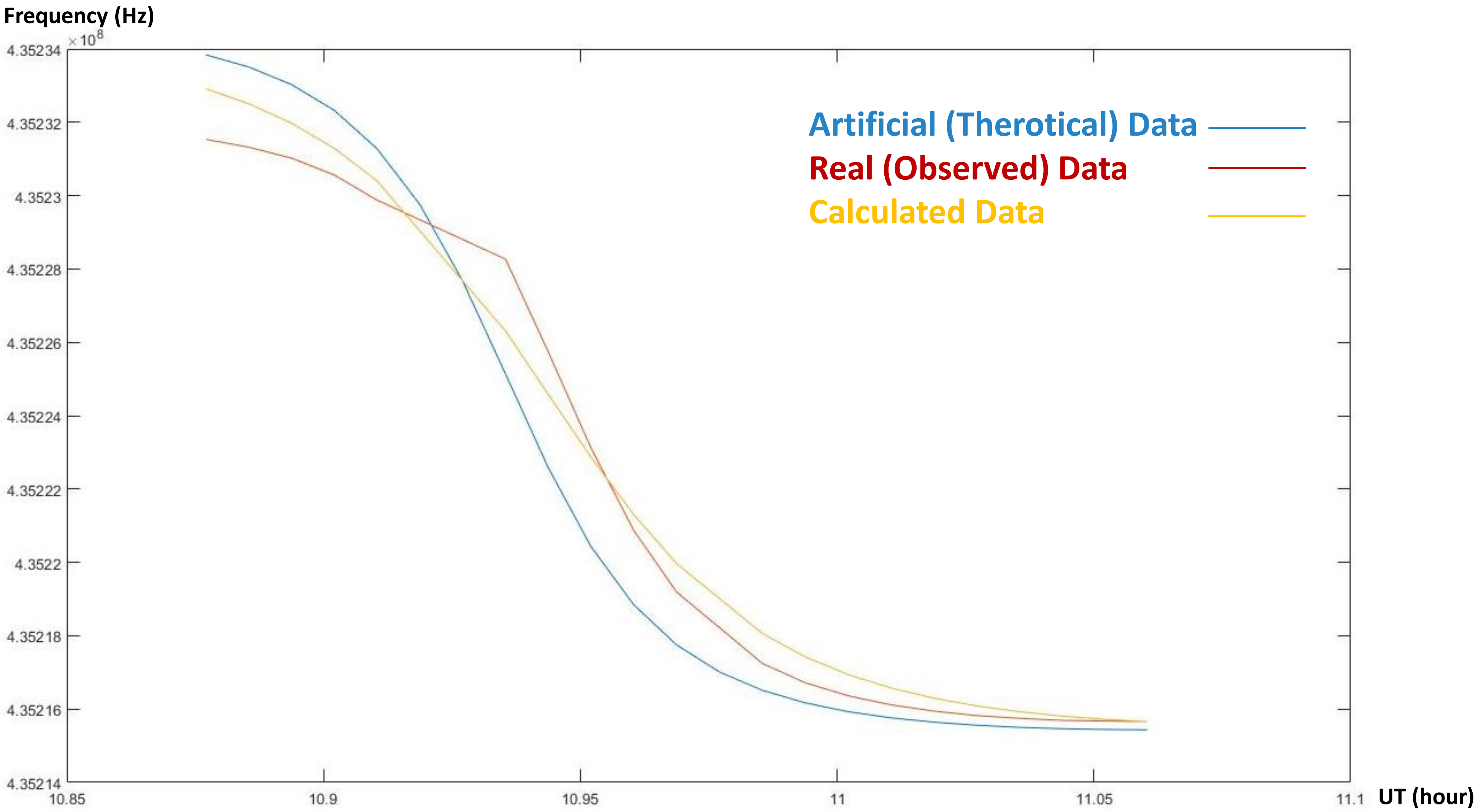
Event	Time	Altitude	Azimuth	Distance (km)	Brightness	Sun altitude
Rises	13:49:06	0°	163° (GGD)	3.320	12,1	60,6°
Reaches altitude 10°	13:51:26	10°	162° (GGD)	2.392	11,5	60,3°
Maximum altitude	13:56:44	83°	75° (DKD)	823	9,8	59,8°
Drops below altitude 10°	14:02:04	10°	348° (KKB)	2.408	11,0	59,3°
Sets	14:04:25	0°	348° (KKB)	3.344	11,6	59,0°



Pass of The Received Signal

https://www.heavens-above.com/satinfo.aspx?satid=25397

Artificial, Calculated and Observed Frequency-Time Graphs of the GO-32



Preliminary Results for Real Data

Obtained best Keplerian Elements after the optimization process for GO-32.

Gurwin Techsat 1B	$RMS\ (km/s)$	$a\ (km)$	e	$\Omega\ (°)$	$i\ (°)$	$\omega\ (°)$	$\theta\ (°)$	$\omega + \theta\ (°)$
Reference	0	7191.0386	0.0000465	170.8631	98.7304	186.0731	174.0447	0.1178
Gradient	0.5694	7150.1339	0	174.5416	90	116.3571	269.9262	26.2833
Absolute Error	0.5694	**40.9047**	0.0000465	**3.6785**	**8.7304**	69.7160	95.8815	26.27152

Results

- ✓ Usage of gradient optimization with genetic optimization can give accurate results according to an uniformed situation about satellite.
- ✓ Circularity of the orbit increases accuracy of the results.

Future Works

Find a better way to obtain frequency-time data from real observations → Try different propagation methods to improve accuracy → More tests with real data → Check multi-station or multi-pass cases → Prepare repository

OPEN COLLABORATION

Reference

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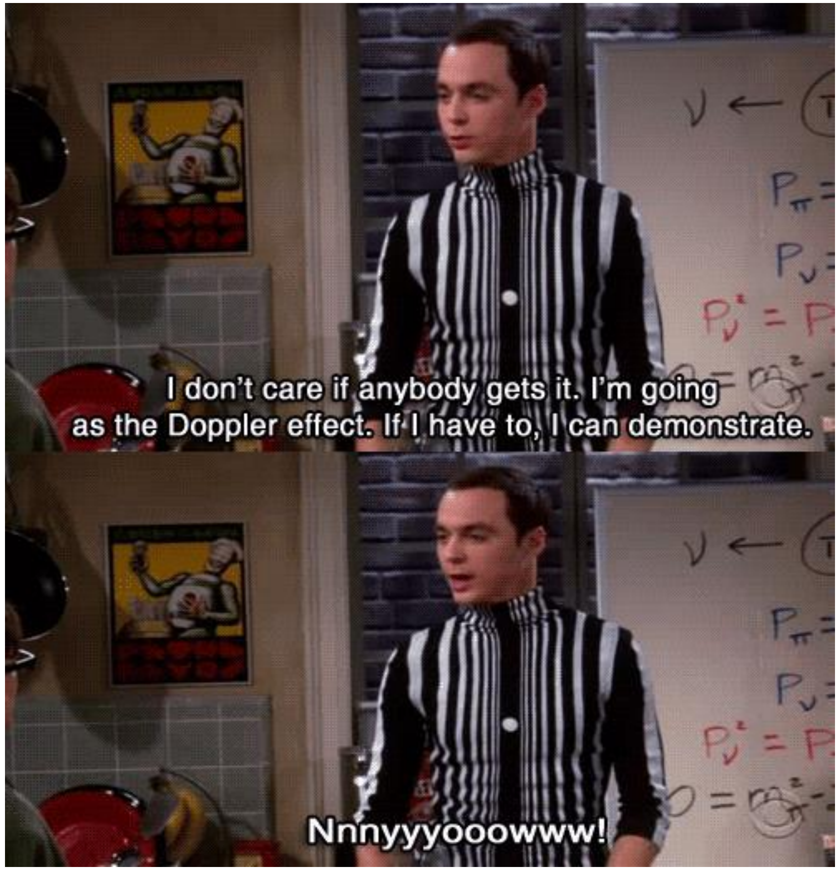
Doppler Based Orbit Determination with Optimization

Thanks!

Questions & Comments



https://imgur.com/gallery/yeGXKVz/comment/34957483

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