Passive RF in Support of Closely Spaced Objects Scenarios

Kameron Simon

Kratos

Abstract

In the Space Domain Awareness (SDA) mission area, particularly with geosynchronous orbits, there are primarily two phenomenologies in the existing Space Surveillance Network (SSN) and commercial market used to observe, measure, and characterize Closely Space Objects (CSO): ground based radar and electro-optical sensors. These phenomenologies and capabilities are well known in the SDA community, but have some short falls. This paper will present and highlight the unique abilities of a powerful SDA phenomenology, passive Radio Frequency (RF). Passive RF antennas can be used in support of CSO scenarios for the purpose of unique satellite identification and ephemeris generation with maneuver detection. It will cover the unique, highly accurate, non-cross-tagged measurements used for orbit determination and maneuver detection by observing each satellite's own RF transmissions. Included will be real world commercial examples used to highlight this capability and a discussion of the analytics.

CLOSELY SPACED OBJECTS

In the Space Domain Awareness (SDA) mission area, particularly with geosynchronous orbits, there are primarily two phenomenologies in the existing Space Surveillance Network (SSN) and commercial market used to observe, measure, and characterize satellites; ground based radar and electro-optical sensors. These phenomenologies and capabilities are well known and understood in the SDA community; however, passive Radio Frequency (RF) sensing has unique, albeit not as well-known, abilities that can be used to support generating highly accurate non-cross-tagged measurements that can be utilized for orbit determination and maneuver detection as well as spacecraft identification.

Today, satellites often fly in Closely Spaced Objects (CSO) scenarios whether or not it is intentional. Some examples of this include the Mission Extension Vehicle (MEV-1) that has a mission of docking to another satellite to extend the life of that satellite, the Luch Olymp satellite that has been known to fly around several satellites in the geosynchronous belt, and the Anik geosynchronous cluster. This paper will focus on two vehicles in the Anik cluster, located around 107.3°W.

The identification of each unique satellite during a CSO scenario in the geosynchronous belt is difficult due to the fact that the primary means of doing so is from ground-based radars or optical telescopes. Oftentimes, these resources cross-tag measurements, are unavailable during solar or weather exclusions, or are not geographically located where they can apply their capabilities. Moreover, they can be expensive to operate. This means the measurements used during the orbit determination process to create ephemeris or two line element sets (TLEs) do not accurately represent the location of each satellite. Not knowing or understanding the exact locations of satellites with respect to each other leads to not detecting maneuvers until long after they have occurred and consequently safety of flight concerns. This also introduces a higher probability of losing custody of the satellites. In a geosynchronous orbit, the primary data is optical. Radar data becomes more expensive and difficult due to the distance from the surface of the earth to the geosynchronous belt. The optical solution enables the accuracy of the TLEs to be within a few hundred meters during tracking and a few kilometers after propagation - even during a best case scenario where there are no other objects nearby. When objects become in a real close proximity scenario such as less than 1 km the identification problem becomes worse, as both optical systems and radar systems are unable to detect that there are multiple objects when they are that close together.

Closely Spaced Object Scenario

The Anik cluster consists of 3 satellites:

- Anik F1 (26624)

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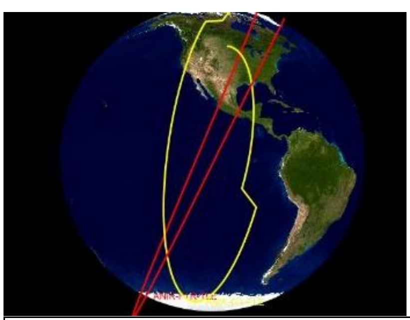
    - Canadian satellite that is based on Boeing's BSS-702 model. The satellite carries 84 transponders: 36 in C-band and 48 in Ku-band. The spacecraft provides general telecommunications services for North and South America. Anik F1 was launched in late 2000 on an Ariane-44L H10-3 rocket.

- Anik F1-R (28868) satellite of interest for the paper
    - Canadian satellite that is based on Eurostar-3000S model. The satellite carries 56 transponders: 24 in C-band and 32 in Ku-band. The spacecraft provides general telecommunications services for North America. Anik F1R was launched in 2005 on a Proton-M Breeze-M rocket. In addition, a Wide Area Augmentation System (WAAS) navigation package operating in C-band for uplink and L-band for downlink provides precision Global Positioning System-based guidance information.
- Anik G1 (39127) satellite of interest for the paper
    - Canadian satellite that is based on Space Systems Loral SSL-1300 model. The satellite carries 52 transponders: 24 in C-band, 28 in Ku-band, and 3 in X-band. The spacecraft provides general telecommunications services for North and South America. Anik G1 was launched in 2013 on a Proton-M Breeze-M rocket.

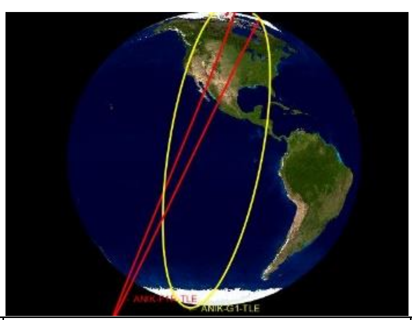
All the satellites in this cluster provide some form of communication or entertainment to users on the earth and they all fly in proximity to each other. Fig. 1 shows a time lapsed images of the publically available TLEs for Anik F1-R and Anik G1 over a seven day time span starting on 18 August 2020 12:00:00 UTC and going to 25 August 2020 00:00:00 UTC. In the daily images, several discontinuities are clearly observable. Each of these discontinuities is from a new TLE being available. The orbit should not experience these discontinuities or change shape dramatically in a standard update when the satellite is following natural motion. However, a discontinuity is expected when the satellite experiences an acceleration caused by performing a maneuver. There are only two maneuvers in this time span both of which are for Anik G1. All of the other discontinuities are believed to be caused by cross-correlated measurements or cross-tagging. These cross-tagged measurements are then fed into the orbit determination process which in turn generates TLEs that are not completely representative of the actual orbit.

Day 1
18 Aug 2020 00:00:00.00
to
19 Aug 2020 00:00:00.00

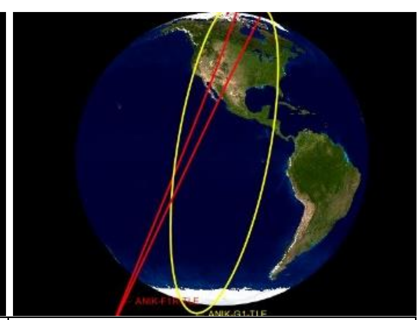
Legend



Day2
19 Aug 2020 00:00:00.00
to
20 Aug 2020 00:00:00.00



Day3
20 Aug 2020 00:00:00.00
to
21 Aug 2020 00:00:00.00



Day 4
21 Aug 2020 00:00:00.00
to
22 Aug 2020 00:00:00.00

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Day 5 22 Aug 2020 00:00:00.00 to 23 Aug 2020 00:00:00.00	Day 6 23 Aug 2020 00:00:00.00 to 24 Aug 2020 00:00:00.00	Day 7 24 Aug 2020 00:00:00.00 to 25 Aug 2020 00:00:00.00

Fig. 1. Public TLEs Time Progression

The two satellites Anik G1 and Anik F1-R were not only chosen as they were part of a cluster, but also because Anik F1-R hosts a Wide Area Augmentation System (WAAS) payload. This WAAS data is compelling, as WAAS is used to augment the Global Positioning System (GPS). This means it reports the position of the Anik F1-R satellite with high accuracy and can be used as a calibrator of the system.

PASSIVE RF COLLECTION SYSTEM

Kratos currently owns and operates a worldwide passive RF collection network that is able to collect in S-band, C-band, X-band, and Ku-band. For the data in this paper the passive RF ranging antennas are located in the United States. The approximate antenna locations can be seen located in Fig. 2.

Fig. 2. Kratos RF Collection Network

PASSIVE RANGING OVERVIEW

Since passive ranging uses the satellites transmitted signal to range the vehicle, the passive ranging system is not restricted by the same limitations that optical or radar systems experience. Passive ranging is able to identify and maintain unique identification of each object when they are in close proximity or even docked together. Passive ranging, along with orbit determination, supplies accurate satellite position and velocity without the need for transmissions from the ground to the satellite, satellite cooperation, specialized satellite payloads or detailed knowledge of ranging signal structures. However, it does require that the satellite has an active RF signal. This could be a telemetry, tracking, and control (TT&C) signal, beacon signal, or a payload signal.

The passive ranging system calculates the satellite's position by executing precise co-collects from multiple apertures over time. The process involves time synchronized short captures of the raw RF signal data. The raw data is precisely time stamped at a surveyed antenna location. The raw data is then time and frequency aligned across all the antennas. Using these signal captures, Differential Time Offset (DTO) and Differential Frequency Offset (DFO)

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measurements are made between all capture sites. DTO represents the difference in time that it takes the satellite's signal to travel from the satellite to the receiving ground stations through the RF equipment to the digitizers, while DFO represents the difference in frequency of the signals received at the ground stations. DTO is typically measured in seconds. DFO is typically measured in Hertz. Three or more spread out capture sites are needed to perform orbit determination using only DTO and DFO data; however, using measurements from other phenomenologies, orbit determination could be done with just two locations. The concept behind DTO and DFO collection is shown in Fig. 3 and Fig. 4.

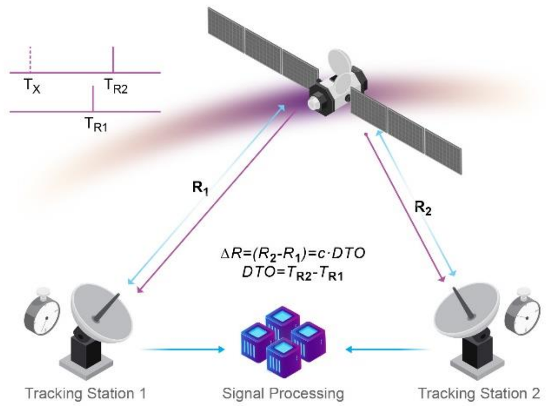

Fig. 3. DTO

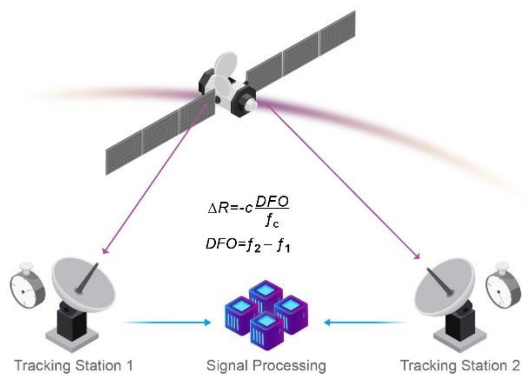

Fig. 4. DFO

The characteristics of each satellite transmitting a distinctive waveform create a unique time delay which allows the system to determine the directional movement relative to other satellites in close proximity. Since the passive ranging signals come from the satellite itself, it is useful in real time satellite detection, tracking, identification, maneuver detection, and characterization operations. This includes attribution, differentiating CSOs, custody, and maneuver detection when other sensor types cannot "see" the object of interest.

CLOSELY SPACED OBJECTS EXAMPLE DATA

Fig. 5 shows a plot of the collected normalized DTO data and the normalized DFO data for the Anik F1R satellite. These plot shows the satellite under natural motion without any maneuvers.

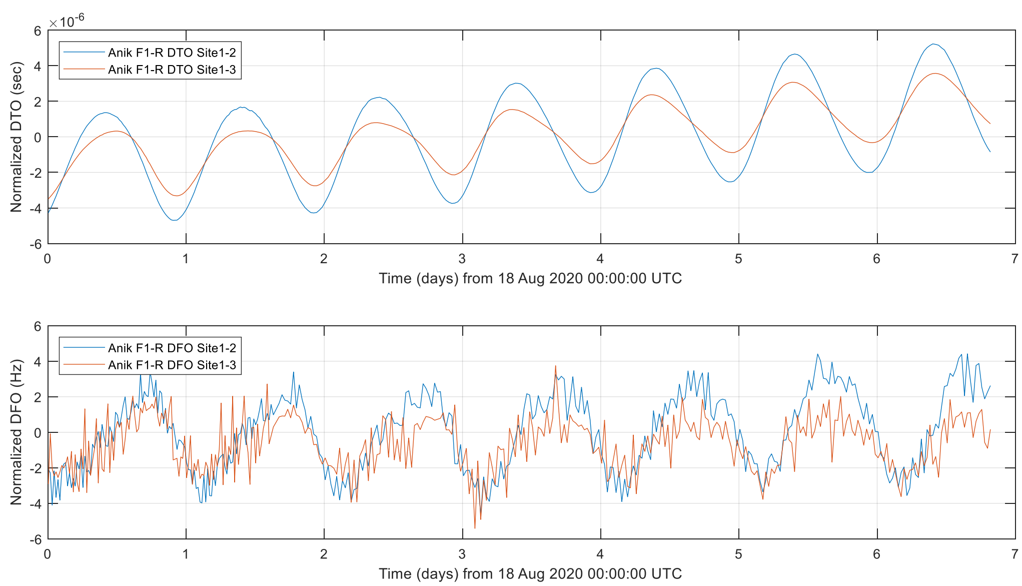

Fig. 5. Anik F1-R Normalized TDOA Measurements

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Fig. 6 shows a plot of the collected normalized DTO data and the DFO data for the Anik G1 satellite. It can be seen that Anik G1 performed a maneuver around 19 August 2020 15:00:00 UTC and then did a follow up trim burn on 20 August 2020 around 18:30:00 UTC.

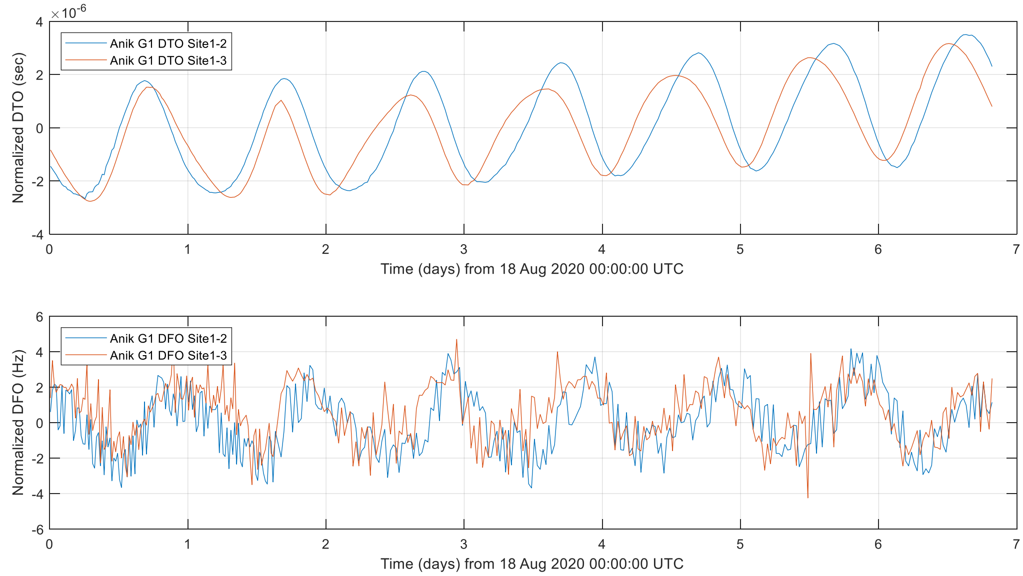

Fig. 6. Anik G1 Normalized TDOA Measurements

The effect of cross-tagging is quite clear in **Fig.** 7, which shows a plot of the Anik F1R publically available TLEs compared to the WAAS GPS provided ephemeris. The TLE solution oscillates between an error of 2km to 20km on the first four and half days. At this point, it appears the cross-tagging ceased, as the error drops abruptly for the last three days.

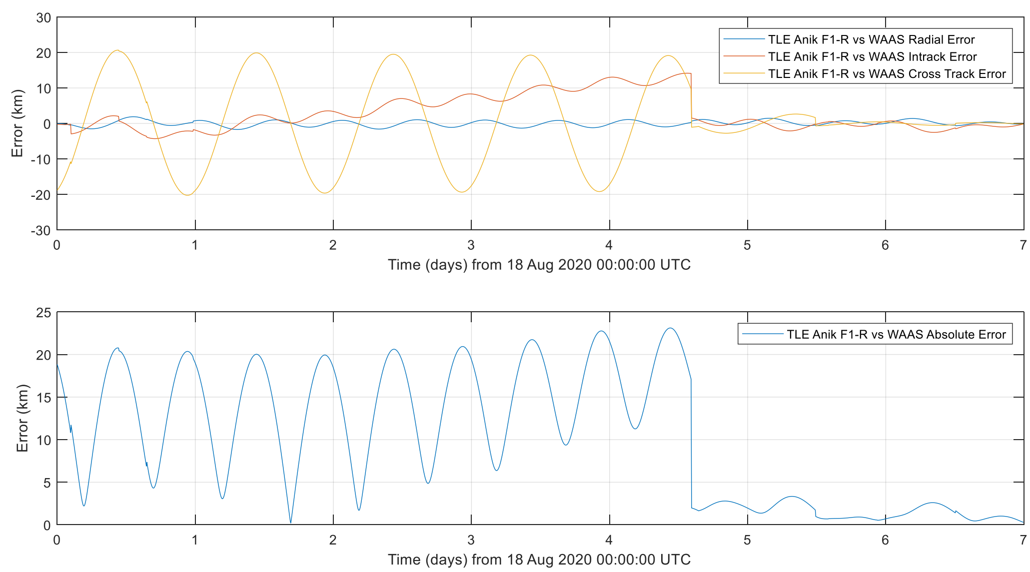

Fig. 7. Error between Anik F1-R TLE and WAAS data

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Fig. 8 shows a plot of the Kratos passive ranging solution for Anik F1-R compared to the WAAS GPS provided ephemeris. In this figure, the Kratos passive ranging solution is within 250 meters throughout the data set. The average error of the TLEs compared to the WAAS GPS data is 11.5km. The average error of the Kratos passive ranging solution compared to the WAAS GPS data is 0.0874km. This results in a 131.6x improvement in accuracy.

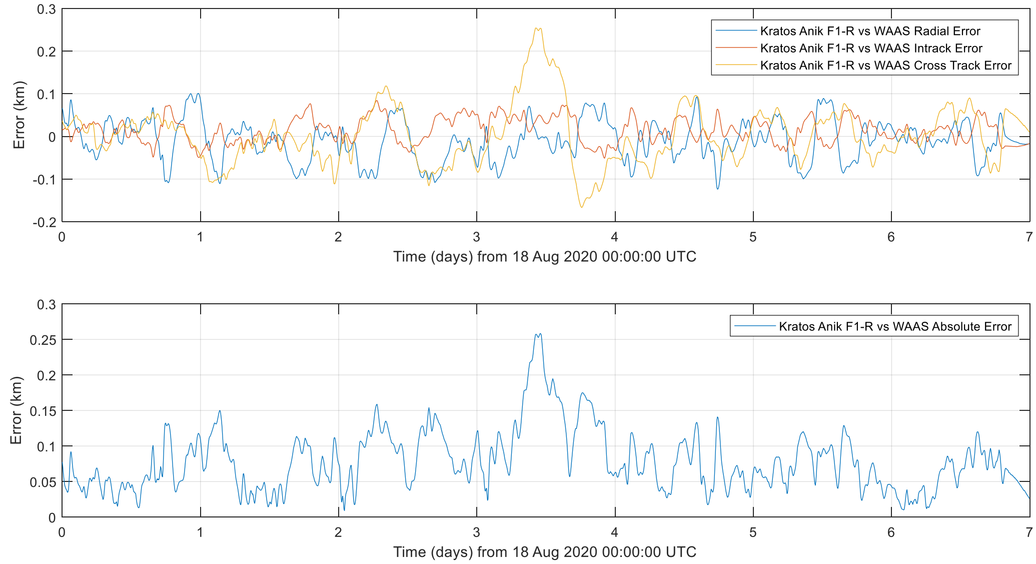

Fig. 8. Error between Anik F1-R Kratos Solution and WAAS data

Fig. 9 shows a plot of the Kratos passive ranging solution for Anik F1-R compared to the publically available TLEs. The figure shows the discontinuities in the TLEs around 0.1, 0.4, 0.65, 4.5, and 5.5. The Anik F1-R WAAS data shows that the satellite never maneuvered during this time frame, and so it is assumed that the TLE error is from cross-tagged measurements used in the orbit determination process.

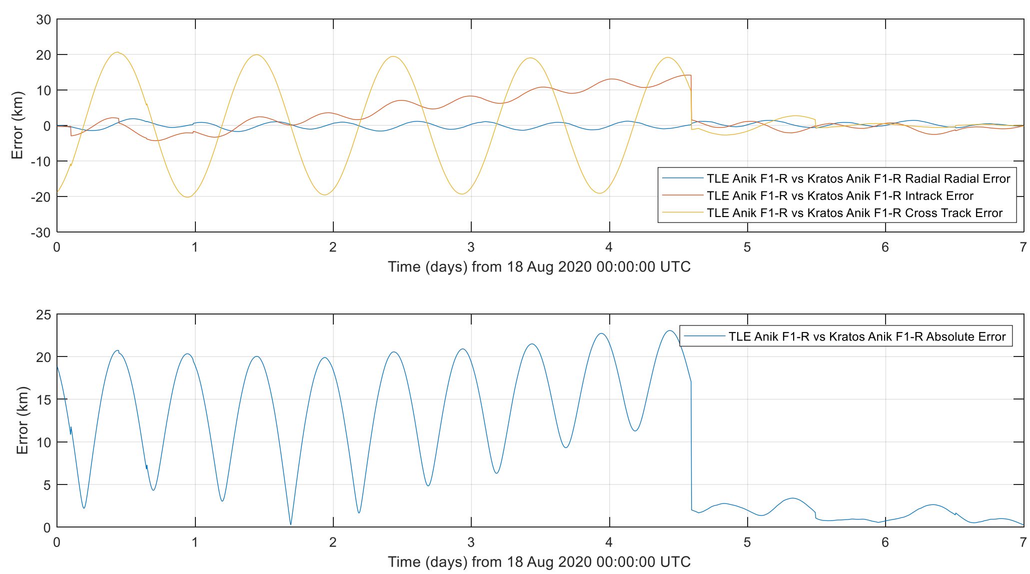

Fig. 9. Difference between Anik F1-R Kratos Solution and Anik F1-R TLE

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Fig. 10 shows a plot of the Kratos passive ranging solution for Anik G1 compared to the publically available TLEs. The figure shows the discontinuities in the TLEs around 0.15, 0.4, 1.2, 1.6, 4.5, and 5 days. Since Anik G1 maneuvered around 19 August 2020 15:00:00 UTC with a follow up trim burn on 20 August 2020 around 18:30:00 UTC. Some discontinuities around those times are expected but not the others. Even looking at after the maneuver you can see how the public TLEs take approximately two and half days to recover from the maneuver. Once the maneuver error is removed, the solution still oscillates between 1km and 13km of error and has other discontinuities. At the very end of the data set the orbit starts to have the right shape which brings the error down.

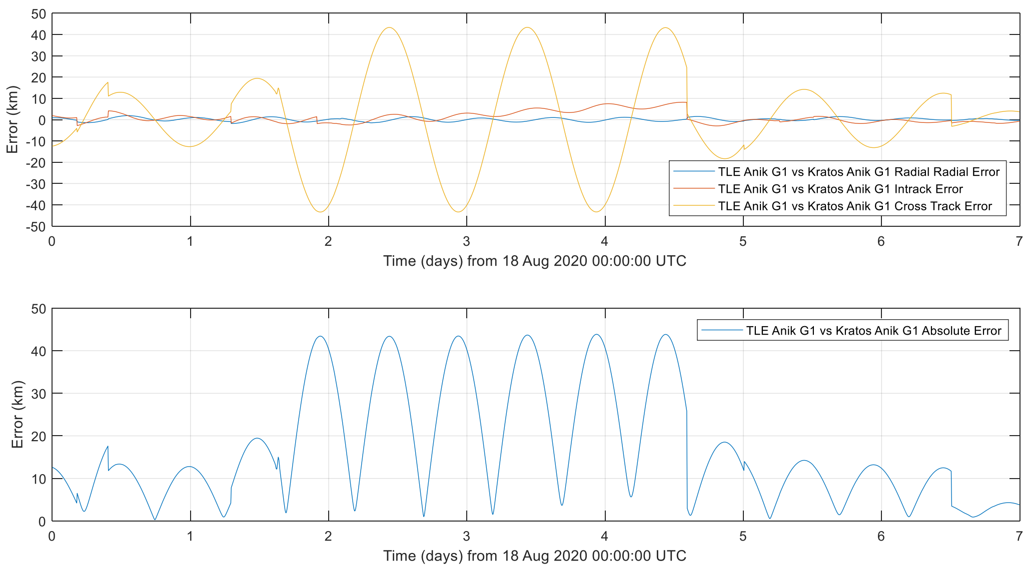

Fig. 10. Difference between Anik G1 Kratos Solution and Anik G1 TLE

CONCLUSION

Fig. 11 shows the same data as Fig. 1, but now the Kratos solution is also shown. When comparing the shapes of the orbits on the first day, it is clear that there is a big difference between the Anik F1-R Kratos solution and the TLE Anik F1-R solution. There was no maneuver in the data set for Anik F1-R, so all orbital errors can be attributed to cross-tagged objects. The second day through the fourth day show a similar error in the orbit shape and location to that shown in day one. The fifth day does an abrupt change to get to a shape that gets closer to truth. The sixth through seventh days show the TLE solution starting to converge on a good solution for Anik F1-R. However, the solution is still several kilometers off. The Kratos passive ranging solution follows the WAAS GPS data so closely that the difference cannot be seen on any of the days. Kratos has also worked with other vendors to verify the accuracy of their results along with comparing to the WAAS GPS data.

When comparing the shapes of the orbits on the first day for Anik G1, it is clear that there is a big difference between the Anik G1 Kratos solution and the TLE Anik G1 solution. Comparing the second shows that the TLE solution for Anik G1 begins to get worse. This is probably due to a maneuver that occurred on 19 August 2020 around 15:00:00 UTC. The trend for the Anik G1 TLE solution continues through days three and four. Day five shows the Anik G1 TLE solution abruptly changing shape to a new orbit that is starting to follow the Anik F1-R solution. Day six shows Anik G1 TLE solution matching the shape and location of the Anik F1-R solution. There have been no maneuvers in the last two days so this is a result of cross-tagging the measurements from Anik F1-R. On day seven after another abrupt change the Anik G1 TLE solution is closer to the Kratos solution, but still does not have the accuracy as a passive ranging can provide.

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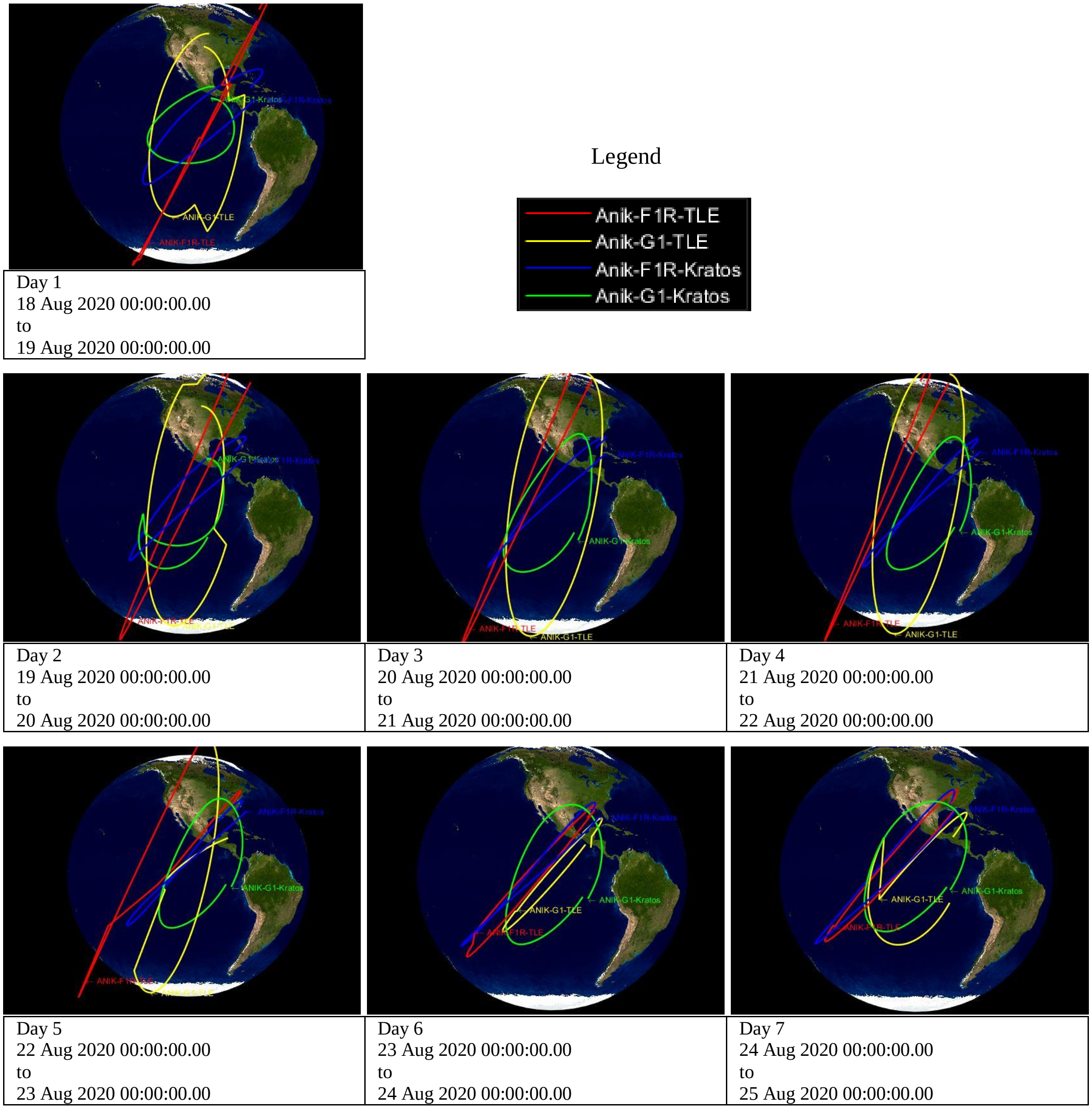

Fig. 11. Difference between Anik F1-R Kratos Solution and Anik F1-R TLE

With the new normalcy of CSO scenarios in the geosynchronous belt, SDA is more important than ever. Due to the limitations of both optical and radar systems when objects fly close together, it is recommended to supplement the SSN and commercial market solutions with passive ranging. Since passive ranging uses the transmitted signal from the satellites it is able to uniquely identify satellites in CSO scenarios even when objects become within 1km of each other or are docked to each other. Passive ranging is available in all weather conditions and 24x7 as it does not have exclusion times. The only limitation of passive ranging is the satellite must be transmitting a signal; however, most active satellites do this today either for TT&C or mission payload systems. Since passive ranging can maintain identity of satellites in CSO scenarios, it can also be used for maneuver detection to provide real time Indications and Warning (I&W). Although the Anik geosynchronous cluster doesn't fly as close as some of the other missions mentioned in this paper, it still shows that the SSN today could not correctly identify measurements or create accurate TLEs of each object during the timespan of interest. Supplementing the SSN with passive ranging data could free up resources to focus on non-emitting space object tracking such as debris while enhancing the accuracy of the current catalog.

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