Analysis of Orbit Residual Behavior to Determine Contact in Rendezvous and Proximity Operations at Geosynchronous Orbit

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INTRODUCTION

A Closely-Spaced Object state is one in which two objects on orbit (one the primary, one secondary) are so close that they fade into the noise of one another and generally the secondary cannot be distinguished from the primary. Ground sensors may lose track of a space object if it enters into a CSO state. However, analysis of orbit residuals may provide insight on the behavior of objects in a CSO state. This paper describes the general theory and gives an example of a CSO pass in MEV-2 and Intelsat-1002.

Non-resolved remote imaging of objects in geosynchronous orbit, if persistent and generating data of sufficient accuracy, may be used to assess the behavior of two closely-spaced objects. In particular, it may be possible to assess whether two objects are conducting proximity operations or whether they have actually made physical contact, via analysis of photometric and astrometric residual information. Initial models of this behavior can be validated against actual data collected from such events, which may become more common in the near-term future. This capability may be useful in space traffic management applications.

1. STRUCTURE OF ORBIT RESIDUALS

1.1 Definition of orbit residuals

An orbit residual is the difference between the mathematically-predicted location of a space object and its actual detected location. Residuals exist because even though the fundamental laws of orbital motion can be expressed in simple analytical form, perturbations of these laws and the mechanics they govern often must be captured in complex mathematical forms, including polynomial series expansions, sinusoid functions, and even stochastic expressions. The forces present in the real world have certain effects on space objects, and some of the higher-order effects of said forces can only be approximately captured in mathematical terms that are of reasonable size and calculability. The differences between the real physical effects of these forces and the expected physical effects predicted by simplified mathematical representations of these forces are the residuals that appear when physical data are overlaid against predicted data.

Analysis of orbit residuals has applications in the characterization and maintenance of accuracy for signals from Position, Navigation, and Timing (PNT) satellite systems [1-2, e.g.], although these applications have limited direct bearing on analysis of CSO states.

While residuals can be reduced in magnitude by the use of an advanced propagation model, they often fall in the range of sub-unity arcseconds for data used in this paper. That is, using sensors, propagators, and other tools at ExoAnalytic's disposal, a typical range of orbit residuals is between +/- 1 arcsec. This value represents an approximate floor for random and unmodeled cyclical and secular error in ExoAnalytic's analytical chain.

1.2 Residual Structure

Two intrinsic factors create inherent structure in residuals: uncaptured dynamics and stochastic error.

<u>Uncaptured Dynamics</u>
Dynamics of motion that are not captured by propagation models vary widely depending on the depth of complexity of the model and the precise characteristics of the orbit being modeled, as different types of dynamical effects

(including gravitational perturbations, effects of moving in and out of eclipse, and atmospheric drag) vary among orbit regimes. Very roughly, uncaptured dynamics are likely to appear as either repeating sinusoidal patterns in residuals (for cyclical effects) or as gradually-increasing growth patterns in residuals (for secular effects). The most prominent secular effect is atmospheric drag, which is effectively not present at geosynchronous altitudes, and thus is not considered in particular detail here.

If uncaptured dynamic effects appear in residuals, they are likely to appear as sinusoidal patterns. If we make the assumption that multiple dynamical effects may be present and all are overlapped, the sinusoidal pattern may be a complex function rather than a smoothly-oscillating curve, but it will still have periodic features.

Stochastic error

Here we consider stochastic error as the sum appearance of errors in measurement caused by fundamental uncertainty and by the ineluctable facts of making real measurements. Without a deep analysis of all possible sources of error, some possible factors include shot noise, atmospheric effects, and minor axial tremor on sensors caused by sensor motion or even by environmental effects.

It is not unreasonable to assume these errors appear in Gaussian patterns. Figure 1 shows the patterns inherent in residuals for data collected from objects with extremely well-described orbits (thus minimizing the effects of unmodeled dynamics); note the fundamentally-Gaussian patterns on the left side of the figure and the two-axis distribution spray on the right.

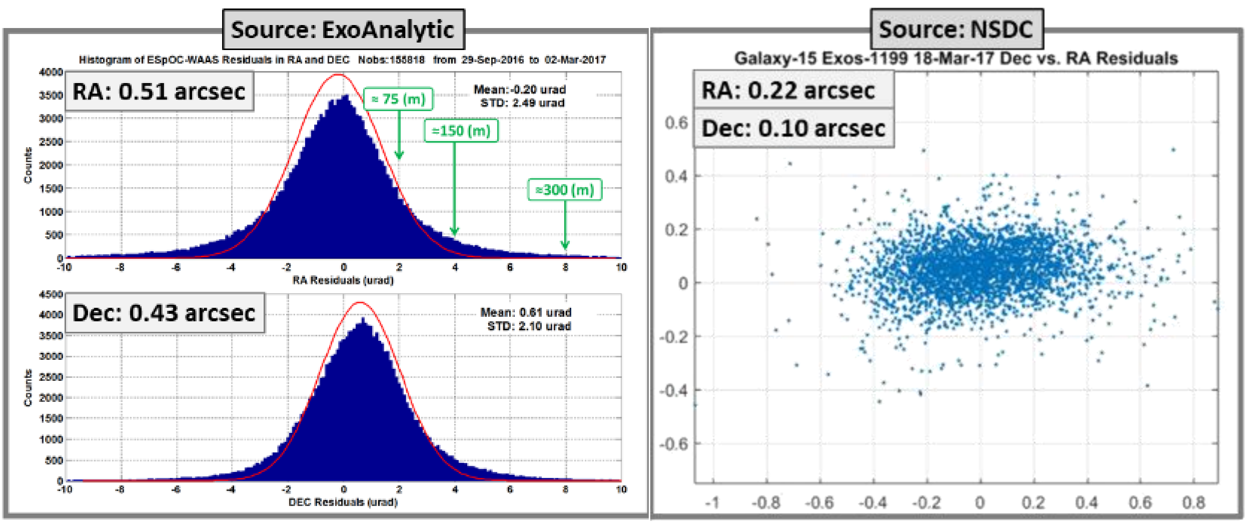

Figure 1. Demonstrated results of ExoAnalytic data, presented in residuals.

Accordingly, the fundamental visible shape of orbit residuals at a given time window ought to include some elements of Gaussian and sinusoidal shapes, for an object that is comparatively well-behaved.

Baseline Residuals Example

Figure 2**Error! Reference source not found.** shows residuals for the ES'Hail communications satellite. The satellite is holding steady in a geosynchronous slot, and as such displays very predictable behavior. The baseline residuals visible in the figure are small and indicate a close match between expected and actual positions.

Note the roughly Gaussian shape of the outer curve of the residuals (barring outliers). The gaps in the figure where no residuals are seen indicate the daylight hours when imaging cannot be conducted from all ground-based sensors due to the solar exclusion, and thus no actual position data is immediately available to compare to predicted position data. Of further note is the fact that the data are voluminous; approximately 13,159 data points are visible in this figure alone.

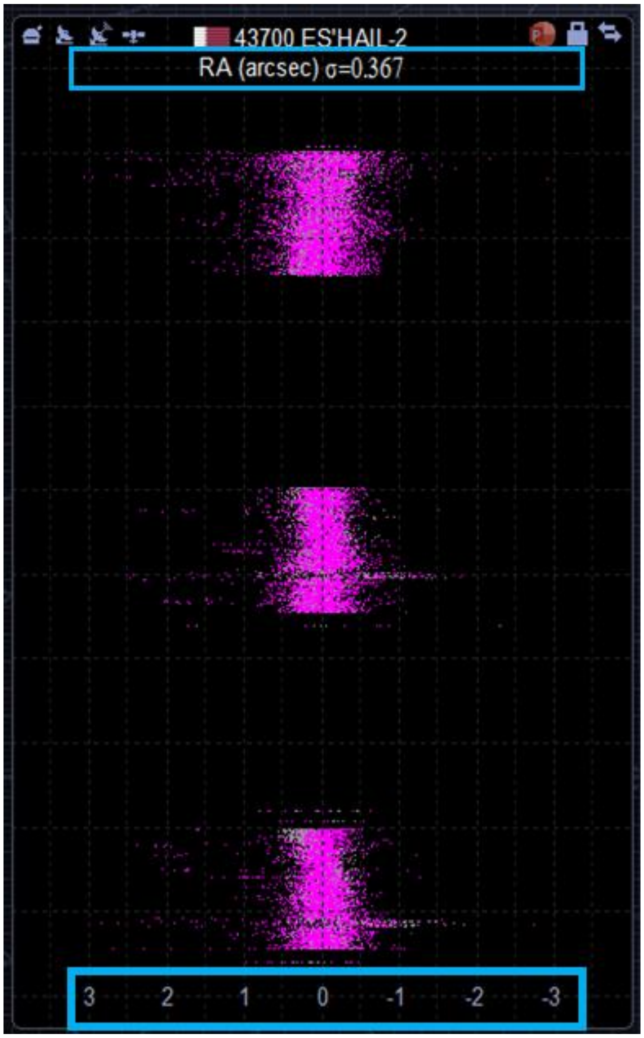

Figure 2. Example of actual orbit residuals from the ES'Hail-2 geosynchronous commsat.

However, other causes of residuals also exist. Of primary interest are residuals caused by the presence and actions of a closely-spaced companion object, which are the main topic of this paper.

1.3 Closely-Spaced Object State

A Closely-Spaced Object condition may be defined as the case where two objects in space are so physically close that the ground-collected sensor image of one overlaps with the sensor image of the other. In this condition, described in this paper as CSO state or as two objects' being CSOd with one another, it is not always possible to distinguish the two.

Objects may enter a CSO state when either in an orbit phase conducting Rendezvous and Proximity Operations (RPO) or when simply making very close flyby passes. If a much dimmer object enters CSO state with a much brighter object, it may effectively disappear. If two objects of similar brightness enter CSO and then later exist CSO, their paths must be disambiguated (by means such as photometric fingerprinting review or by assessing whether orbital paths have altered). If two objects of similar brightness enter a CSO state, it may be difficult to assess their actions toward one another.

One interesting feature of CSO state is that objects in it are not in physical contact: this would instead be a docked state. This leads to the insight that, from residual behavior analysis, it is possible to determine the moment of docking.

1.2.1 Theoretical Expected Residual Structure for Closely-Spaced Objects (CSOs)

To understand why closely-spaced objects (CSOs) may be visible in orbit residuals, and why it may be possible to distinguish between when the two objects are relatively separated, in a CSO state, or docked, we may consider an extremely-simplified view of residuals. Figure *3***Error! Reference source not found.** shows the optical signature of a space object, represented as an orange circle, as it moves along a defined path over time (the image is arranged as a waterfall plot, so time proceeds down from the top edge). The defined expected paths of the object, seen at four separate times, are shown by solid blue lines, and the actual paths of the object are shown by dashed blue lines.

To simplify the figure, the expected path is shown as a vertical straight line. (Any mathematically-defined line that purported accurately to capture the dynamics at play would work as a defined path.) The leftmost section of the figure shows the object moving precisely along this defined path.

The center section of the figure shows the object moving along an oscillatory path, weaving slightly from left to right and back as time proceeds. The path of the center of the object is shown by the dashed blue line.

The right section shows only the two lines: the solid and straight expected path and the dashed, varying actual path. The difference at any point in time between the two lines is the residual at that point in time.

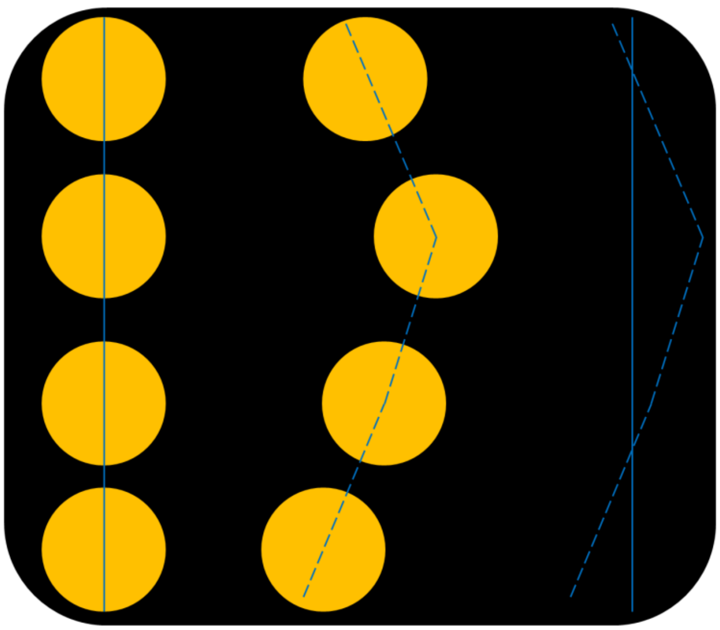

Figure 3. Waterfall plot showing residuals explanation. Left is a straight line tracking the centroid of a notional space object (orange circle, representing the blur spot on the sensor made by the object), center is a variable path indicating unmodeled dynamics, and right is the abstracted paths representing the predicted and actual paths of the centroid. Residuals would appear as horizontal lines indicating the difference in the two.

In Figure 4**Error! Reference source not found.**, two objects nearby one another (but not in CSO state) are represented. One (with a larger circle) is brighter; the other somewhat dimmer. Both are shown as following their own predicted paths closely.

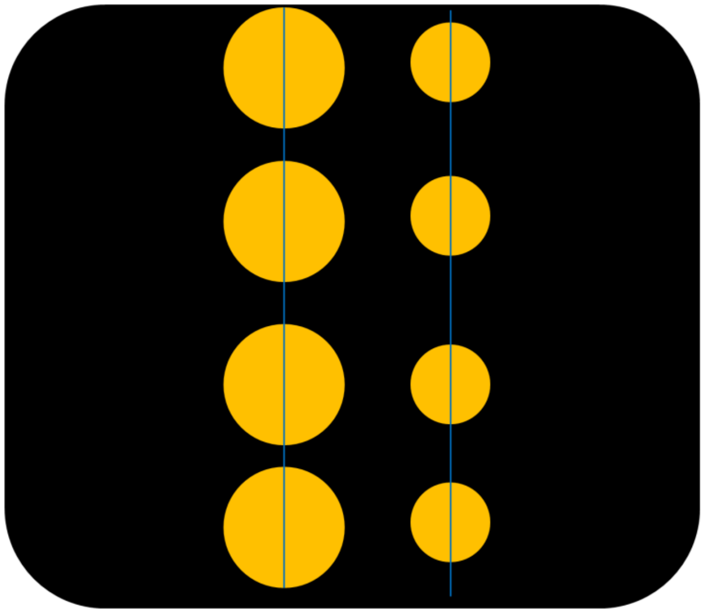

Figure 4. Waterfall plot showing two notional objects with straight lines indicating expected paths.

This state, if detected involving two near but non-CSO objects, could be interpreted as a pre-docking stage, or a nominal state for two objects with related or similar missions.

Next, an example showing behavior in a CSO state is described. In Figure 5**Error! Reference source not found.**, space objects again appear as orange dots, although one is brighter (larger) and the other dimmer (smaller). The solid blue line on the left traces the waterfall plot's predicted path of the brighter object as the dimmer engages in an RPO (rendezvous and proximity operations) flight path about the brighter. The center element shows the same RPO with a projected blur spot (white underlay). In CSO situations, the two objects cannot reliably be distinguished, and the underlay represents the actual detected signature. The rightmost element shows this clearly, with a dashed blue line indicating the apparent path of the centroid of the blur spot.

Note that the predicted path and the actual path now show some deviation, which would produce residuals, although this is due entirely to the presence of a CSO in RPO, rather than actual deviation. Thus, some element of the visible residuals can be attributed to a CSO; conversely, the detection of such residuals may well indicate a CSO in RPO.

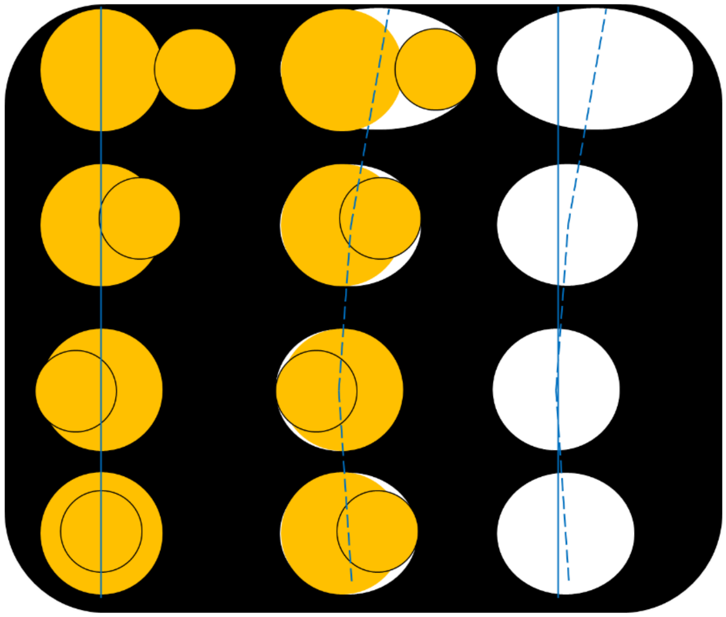

Figure 5. Waterfall plot showing two notional objects in a CSO state. Left: two objects with single line showing predicted path of brighter object; center: two objects overlapped signature showing actual path of detected signature; right: apparent variable blur spot and resulting residuals in overlay of predicted and actual paths. Note similarity to Fig 1.

As a final illustrative description, consider Figure 6**Error! Reference source not found.**, showing on the left two docked objects (orange circles connected by a black X) and their apparent blur spot (the white underlay). On the right, the blur spot and its predicted path once again make a very straight line.

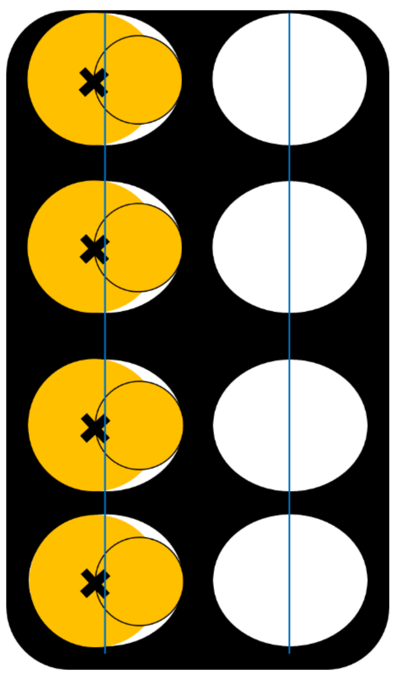

Figure 6. Waterfall plot showing expected state for two space objects in CSO when they are docked. Note similarity to a single object's signature.

The overall trajectory of the residuals suggests a notable evolution in behavior of residuals for two objects in CSO: separately low residuals (when good sensing is available for both), followed by an apparent spike in residuals of one object (and the disappearance of the other) as they move into CSO/RPO, and then finally a drop in residuals as they dock and then begin to behave essentially as a single object again.

That is, if a primary object is approached and CSOd by a second object, the primary object's orbit will show a characteristic residual pattern caused by the motion of the second object near it. If there is a point at which these residuals collapse into a pattern approximating the primary object's original residuals, then this is evidence that docking has occurred and physical coupling is now present.

2. EXAMPLES OF RESIDUAL STRUCTURE ANALYSIS

To illustrate residual structure, we can examine cases where residuals clearly show a maneuver occurring, and where residuals show two objects passing into a CSO state.

2.1 Maneuver Detection in Residuals

Figure 7, below shows an example of the way the orbit residuals may suddenly spike when events occur. The figure shows the right ascension (RA) residuals for Galaxy 16 on the nights of 13, 14, and 15 August 2022. Galaxy 16 maintained a straightforward orbit the first two nights (displaying residuals on the expected order of <1 arcsec), and then performed a small maneuver of approximately 1.0 m/s (which is typical of standard stationkeeping behavior), after which point the orbit residuals spiked to values exceeding 20 arcsec or more.

This element of residual structure is commonly used to detect maneuvers. Note that in many cases, residuals appear in both the RA and declination (DEC) data sets, depending on whether the maneuver altered inclination as well as other orbital parameters. For the sake of simplicity, whenever differences in RA and DEC are unspecified in this paper, they may be assumed to apply to both, although most data shown is only RA residuals.

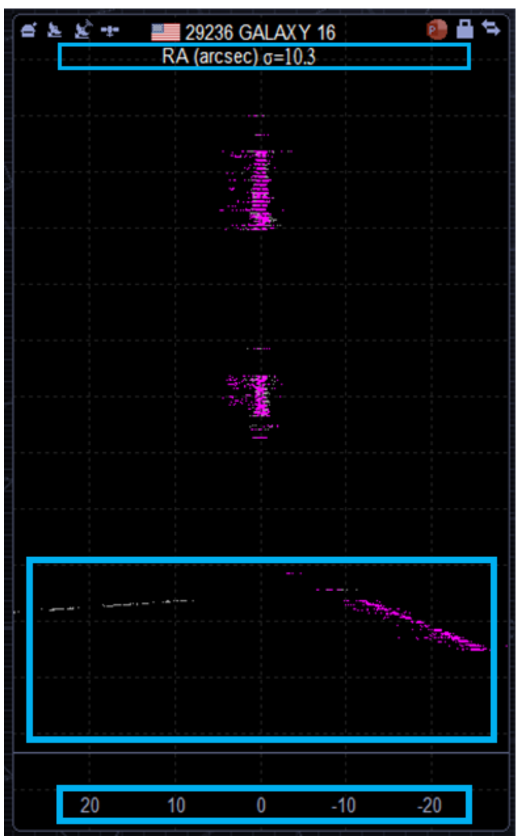

Figure 7. Residual spike in Galaxy 16 following execution of a maneuver (callout box at bottom).

2.2 CSO State Detection in Residuals

In this type of motion, two objects approach so closely as to enter a CSO state, and the residuals of one of these (whichever is the primary) begin to show noticeable effects. Although many objects in orbit pass sufficiently close as to enter, if briefly, into CSO states, here we use the example of MEV-2 and Intelsat-1002.

2.2.1 MEV-2 and Intelsat 1002

A walkthrough of residual behavior in the case of CSOd objects can be illustrated via the example of MEV-2 and Intelsat-1002. In early February of 2021, MEV-2 made a close approach to Intelsat-1002 in a flyby maneuver presumed preparatory to further engagement and servicing. Figure 8 shows this close pass.

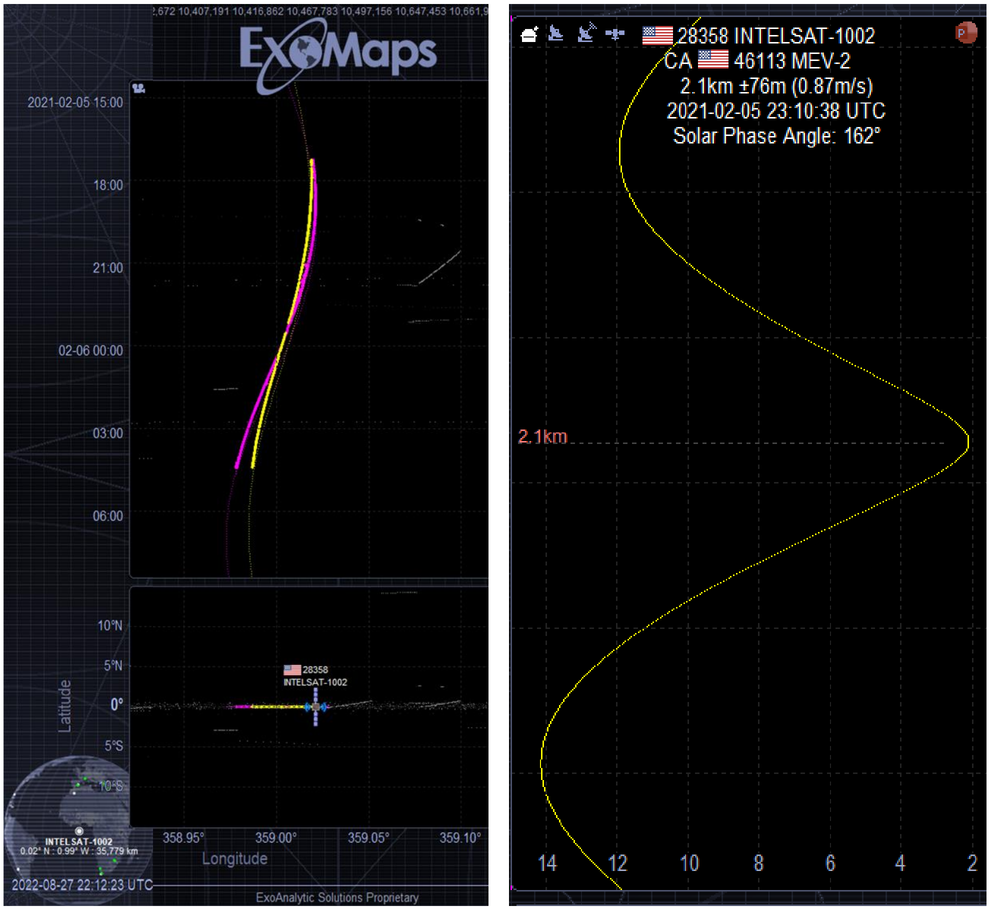

Figure 8. Close pass on night of 05-06 Feb 2021. MEV-2 in yellow, Intelsat-1002 in blue (left). Closest approach was estimated at 2.1 km (right), at approximately 2310 UTC on 05 Feb 2021.

Note the roughly sinusoidal curves of the two orbits in space, shown on a waterfall plot as they cross. MEV-2 is in yellow, and Intelsat-1002 in blue.

Figure 9 shows the baseline residuals on both of these space objects, as captured on a previous night (when such a close pass did not occur).

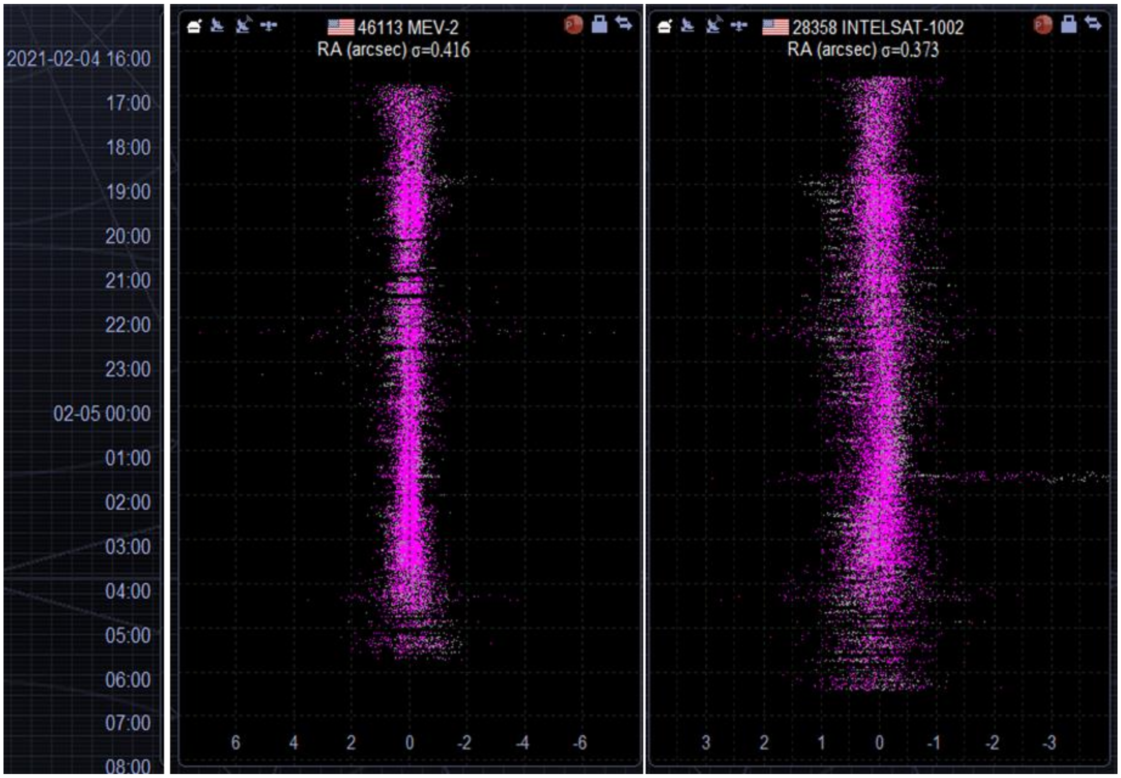

Figure 9. Residuals for MEV-2 (left) and Intelsat-1002 (right) on 04-05 Feb 2021. These are typical residuals for objects in steady geosynchronous orbits.

Note the scales (denoted in arcsec) along the bottom of the image – MEV-2 has residuals of approximately 2 arcsec, and Intelsat has residuals of approximately 1 arcsec.

During the close pass on the night of 05-06 Feb 2021, the blur spots of the two objects overlapped, as detailed in the chip from ExoAnalytic sensors, shown in Figure 10.

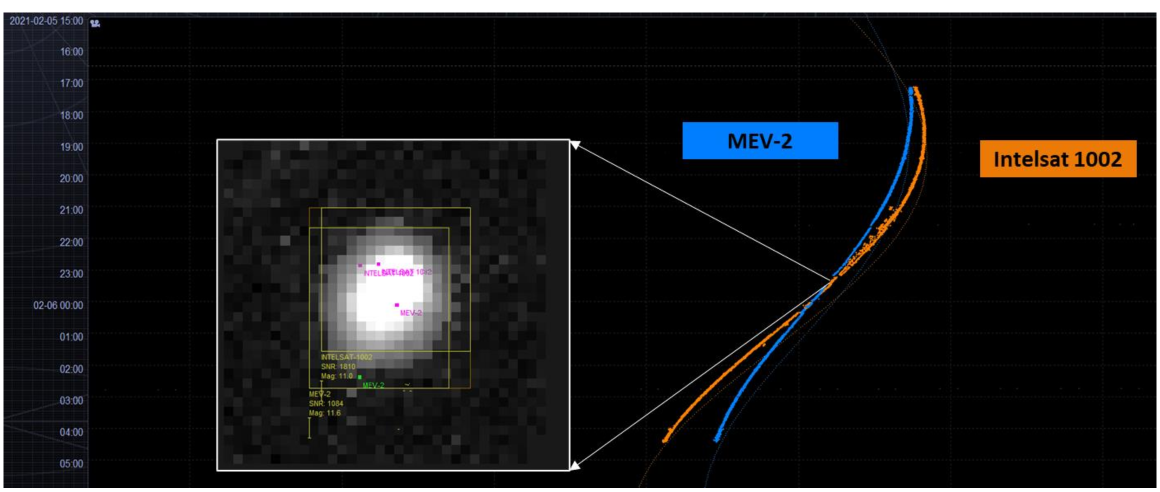

Figure 10. Image chip from close approach of MEV-2 and Itselsat-1002. Note high degree of overlap of blur spots.

During the course of this close approach, the following residual structure was observed.

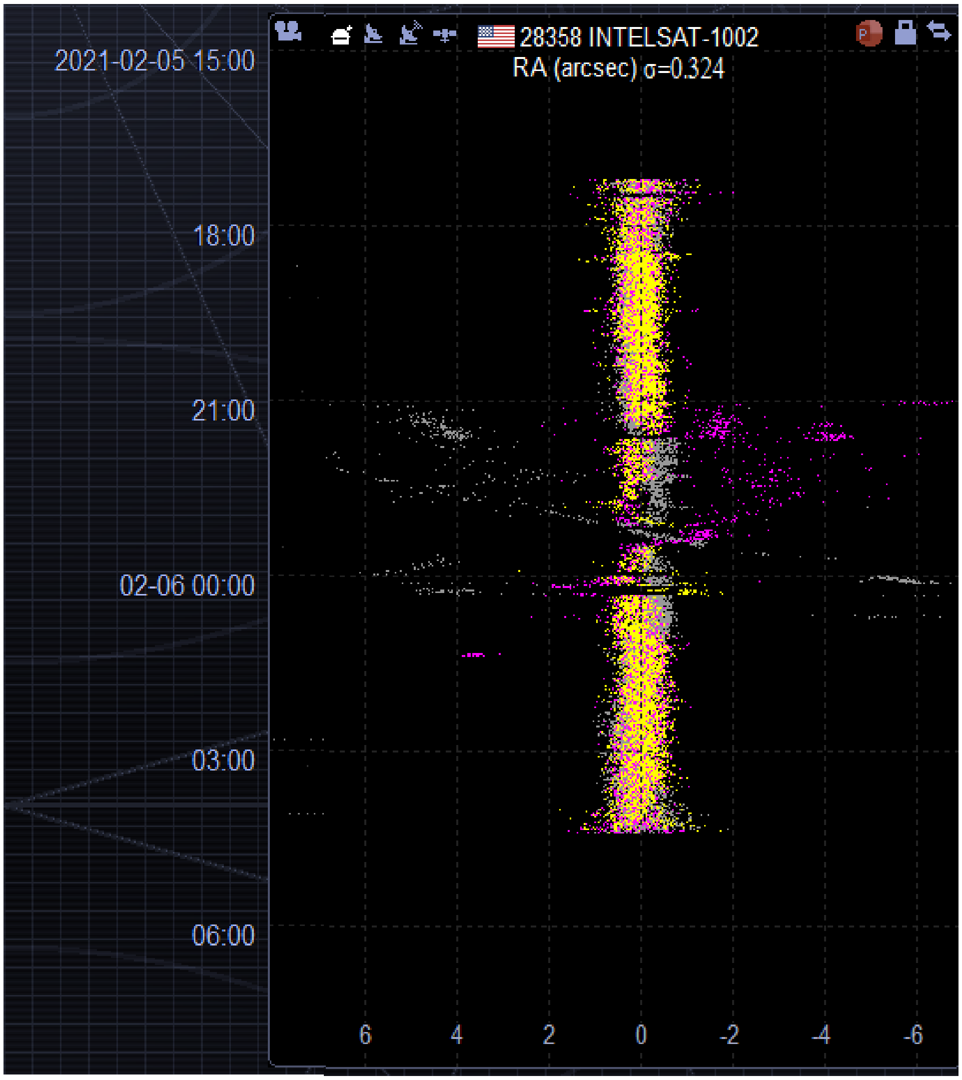

Figure 11. Image chip from close approach of MEV-2 and Itselsat-1002. Note high degree of overlap of blur spots.

Notice the highly-salient residual spikes between 2100 UTV and 2400 UTC; these show that there is a signature of a second object present. It is apparent upon review that the two objects did not dock; later data showing an increasing separation distance between the two objects later in the same night – it is not probable that they briefly docked or made contact and then decoupled.

Note also the short duration of the spike region in residuals (about 3 hours, or roughly one-eighth of an orbit) and the phantom single sinusoid wave apparent in the residuals – these suggest a single pass, with the primary's residuals being pulled first in one direction, then in another, and then disappearing as the CSO state ends.

2.3 Hard Docking Detection in Residuals

In this type of motion, two objects in a CSO state approach to an extreme close position and make hard contact, physically and rigidly joining their structures. This motion corresponds to the types of docking maneuvers common in human spaceflight since the Apollo program, and is exemplified in commercial spaceflight by the MEV-1 and MEV-2 spacecraft operations.

An object physically hard-coupled to another object, particularly if neither of the two are exceptionally large, is effectively one single object from the point of view of a ground observer. From an orbital mechanics perspective, this is also the case; both objects orbit as one. If both objects are physically and rigidly coupled, their blur spots will overlap essentially entirely. At that point, any orbit residuals for the primary object should return to the state they displayed prior to entry into CSO, effectively collapsing again. Residual collapse would only not be expected in two relatively extreme cases: where the physically-coupled objects are continuing to make active adjustments (such as moving into a new orbit, or, less auspiciously, experiencing an imperfect coupling of control systems and physically responding with small attitude adjustments that may be visible as orbit changes).

Figure 12 shows the three stages of residual collapse. Initial residuals (overlaid on the same plot) are in the typical range of 1 arcsec (note the standard deviation value of 0.81); CSO but undocked residuals are much less contained, spreading to 8 arcsec (with a standard deviation value of 3.5), and then docked residuals return very closely to the pre-CSO state. These states appear on successive nights from 10-12 April 2021, as MEV-2 and Intelsat 1002 approach and make docking over several days.

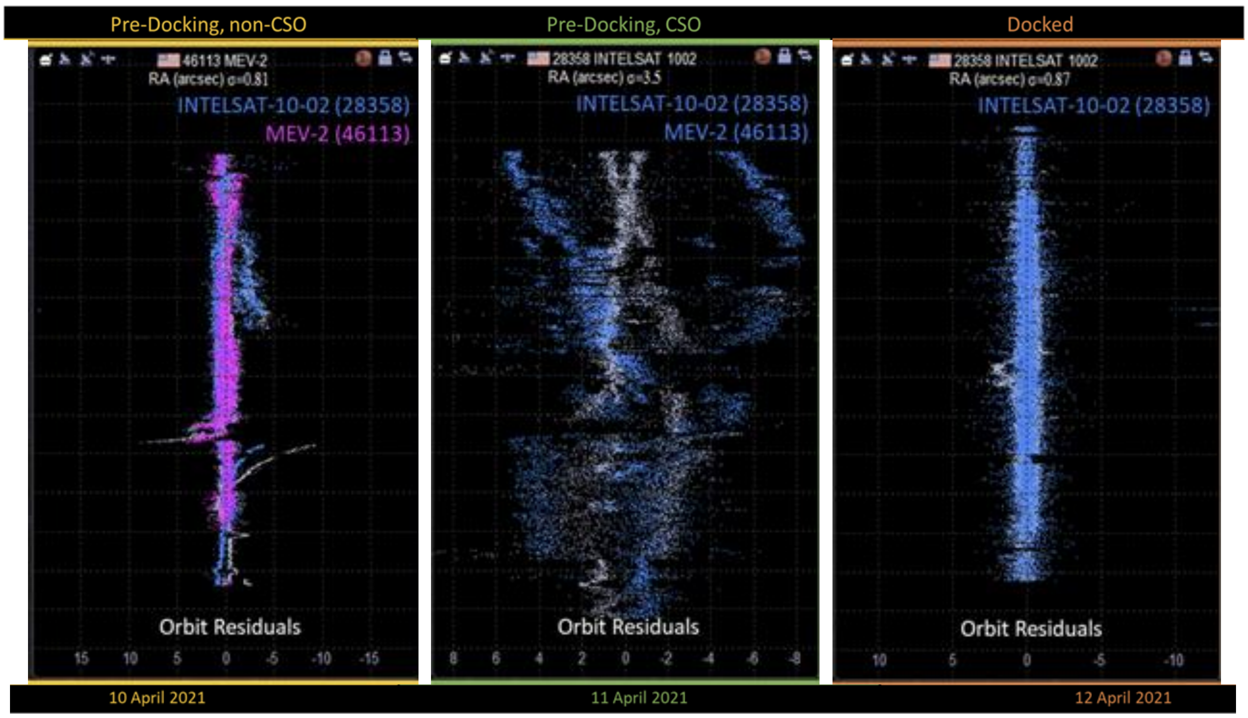

Figure 12. Illustration of residual collapse upon completion of hard docking. Left: undocked, non-CSO baseline residuals. Center: CSOd, pre-docked. Right: docked residuals, collapsed to an undocked level.

A physical coupling with an extremely long joining element (say, a kilometer-scale girder) could conceivably display hard docking behavior without full overlap of the blur spots; however, this is unlikely. The longest artificial structure presently in space is the International Space Station, which is under 110 meters in length. Any physical member joining two objects further apart than this is likely to require substantial novel expertise in stowage and spaceborne deployment and may introduce challenging body dynamics. Furthermore, even a single thin aluminum square tube of such a length is likely to mass 150 kg or more, and a complex girder structure would include multiple main members and stringers, as well as associated mechanisms and mass knock-on effects. So, a physical connecting element sufficiently long to allow two objects to hard dock at extreme distance would likely be, if not roughly the mass of one of the objects by itself, then large enough to constitute the primary payload of one.

For these reasons, we can effectively expect the residual structure of two hard-docked objects to mimic the residual structure of a single object (likely whichever of the two has the primary control authority).

3. FEASIBLE FUTURE IMPROVEMENTS

Future work may publish actual examples of observed behavior wherein the precise moment of docking is detected via apparent residual collapse. Residual collapse is the observable event when, following entry into CSO by a second object, the residuals of a prime object begin displaying smear indicative of a CSO, and then suddenly collapse back into their default low state. This shows the precise moment when hard dock between the two objects was achieved, and they began moving as a single object.

Additionally, while current work allows for the capability to detect behavior within the CSO state, improved sensors may allow for additional depth in detected behaviors. Improved dynamics capture and propagation models may allow for further shrinking of the baseline residuals, allowing improved insight into object behavior during CSO state.

Also, future work may capture the dynamics of soft-coupled motion, which involves a physical but non-rigid connection between two objects. This particular type of connection is not known to be well-attested in observation data. Previous experiments have shown that tether connections are not necessarily stable and may be prone to unanticipated breakage [3].

At any rate, single-strand or multi-strand tethers, as well as other structures, or connections based on long strands of adhesives or multi-segmented hard structures with free-moving joints (i.e, a wedge of a Ferris wheel) may show other residual structure.

Capturing the dynamics of a soft-coupled pair (or, in the future, multi-vehicle chain) is a mathematically-complex endeavor, and likely has strong dependency on the specific type and design of the soft-coupling mechanism. A full listing of possible coupling structures and a deep analysis of their dynamics is beyond the scope of this paper.

4. SUMMARY

This paper has described some of the characteristics of orbit residuals and detailed some of the interpretation potential present in same, along with an example of residuals from a close-pass CSO event and an example of residual collapse after a hard docking event.

5. REFERENCES

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