RADARSAT-2 Definitive Orbit Upgrade

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ACRONYMS AND ABBREVIATIONS

CAPPS	Cataloguing and Product Processing System
COTS	Commercial Off-The-Shelf
EDOT	Enhanced Definitive Orbit Tool
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GS	Ground System
ICD	Interface Control Document
IGS	International GNSS Service
INRS	Institut national de la recherche scientifique
InSAR	Interferometric Synthetic Aperture Radar
km	kilometre
m	metre
MDA	MacDonald, Dettwiler and Associates Ltd.
OD	Orbit Determination
ODMP	Orbit Determination and Maneuver Planning
POD	Precision Orbit Determination
RMS	Root Mean Square
SAR	Synthetic Aperture Radar
SPS	Standard Position Solution
UTC	Universal Time Coordinated

1 EXECUTIVE SUMMARY

MDA has upgraded the system used to generate RADARSAT-2 Definitive Orbit data. The upgraded system is called the Enhanced Definitive Orbit Tool (EDOT) and was developed by MDA in 2014 to improve the accuracy of RADARSAT-2's orbit, which leads to superior capabilities for high-precision SAR applications. Extensive testing and validation was performed with EDOT and the results indicate sub meter position accuracy can be achieved with RADARSAT-2 products produced with the upgraded definitive orbit. Near mid-2015, RADARSAT-2's definitive orbit files will be exclusively generated by EDOT and all definitive orbit products generated using the MDA Headquarters system will benefit from the full EDOT implementation. RADARSAT-2 Network station operators wishing to take full advantage of EDOT's orbit accuracy will require the latest version of the SAR processor (CAPPS SAR 1.2), or a processor patch, in order to correct a bias in the reference position onboard the spacecraft. For network stations that do not upgrade, the EDOT definitive files will still be beneficial as the overall accuracy improvement is larger in magnitude than the shift in reference position. The purpose of this document is to introduce the upgraded definitive orbit, the EDOT tool, summarize its performance, and outline the implications for customers and network stations.

2 INTRODUCTION

To improve the quality of high-precision SAR products generated from RADARSAT-2 such as interferometry (InSAR), geolocation, and digital elevation mapping, an effort was made by MDA to develop and implement a new orbit determination (OD) tool, termed EDOT (Enhanced Definitive Orbit Tool). Development and testing of EDOT occurred throughout 2014 and by the end of the year EDOT was incorporated into the daily operations for RADARSAT-2 at St-Hubert. The definitive orbit files produced by EDOT will replace the current definitive orbit files distributed by MDA. In addition to generating all future definitive orbit files, EDOT has also been used to reprocess orbit telemetry for the entire mission resulting in a full catalogue of enhanced definitive-orbit files. Therefore newly acquired products and historical products can benefit from enhanced orbit accuracy when ordered after the EDOT rollout.

3 ORBIT DETERMINATION FOR RADARSAT-2

With the addition of EDOT, there are now three different systems that perform orbit determination for RADARSAT-2. A brief summary of the three tools follows:

1. POD (Precision Orbit Determination)—processed onboard the satellite using pre-processed GPS data and available as the downlinked orbit (X-band). The overall accuracy is better than 10 m, and it is available in real-time. This system produces the RADARSAT-2 ‘Downlinked Orbit’.
2. ODMP (Orbit Determination and Maneuver Planning)—processed on the ground using weighted least-squares filtering with pre-processed GPS data. Generates original definitive orbit files as well as predicted orbit files. The overall accuracy is better than 10 m, and it is available with up to one day of latency relative to the acquisition.
3. EDOT (Enhanced Definitive Orbit Tool)—processed on the ground using raw GPS data. Generates the new definitive orbit files. The overall accuracy is better than 1 m, and it will be available with between one and two days latency relative to the acquisition.

A more detailed summary of the three orbit tools is presented in Figure 3-1.

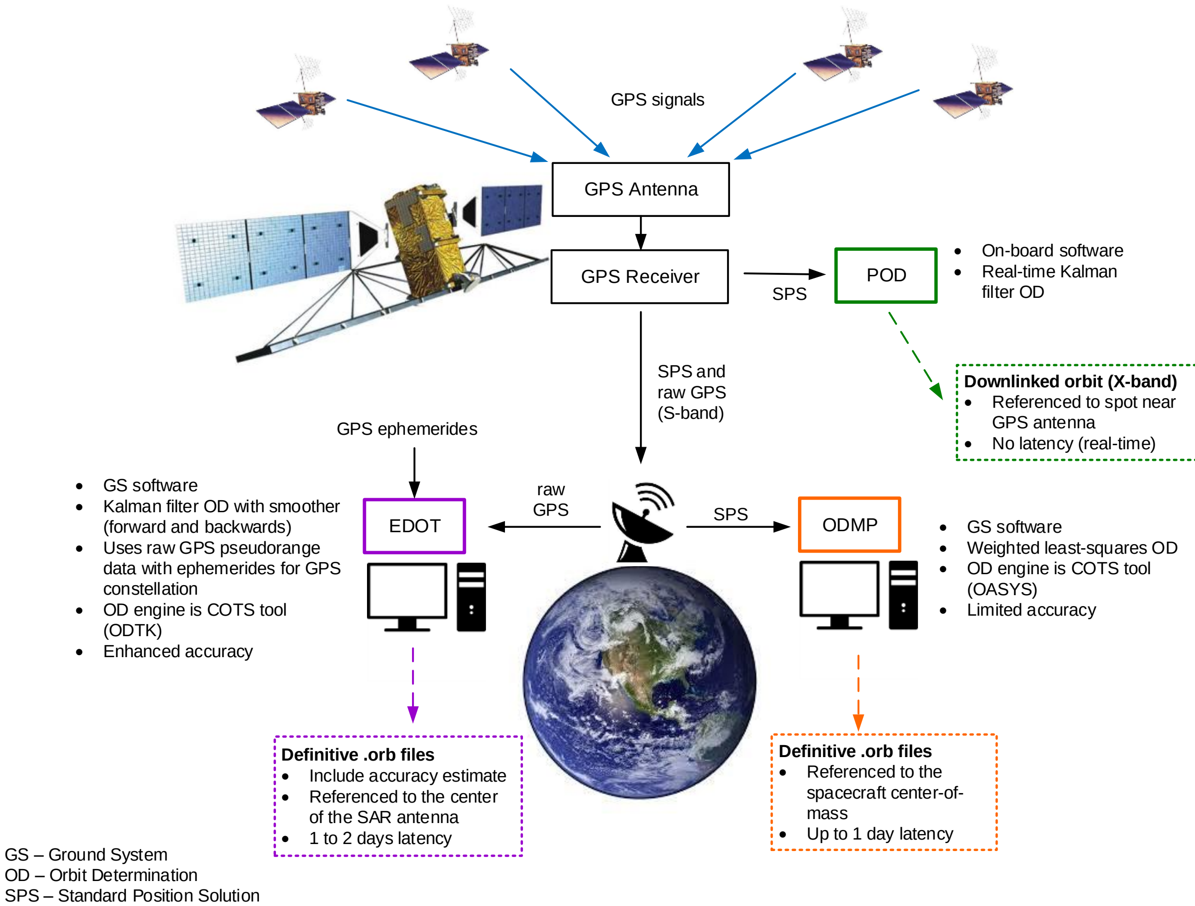

Figure 3-1 Overview of RADARSAT-2 Orbit Determination Tools

4 EDOT OVERVIEW

MDA developed EDOT using several COTS products including STK and ODTK by AGI, and Matlab by Mathworks. The core of EDOT is the orbit determination algorithm in ODTK which uses an Extended Kalman filter and smoother to process raw GPS measurements. The main differences associated with the EDOT orbit solution, apart from the improved accuracy, are the latency of the files, the reference location on the satellite, and the inclusion of an estimate of the solution uncertainty.

4.1 Latency

Because EDOT uses raw GPS measurements, knowledge of the GPS constellation ephemerides at the time of the measurements is necessary for obtaining orbit solutions. Three types of GPS ephemeris are made available from the IGS (International GNSS Service) data centers, the UltraRapid, Rapid, and Final, which have an average latency of about 4 hours, 17 hours, and 12 days respectively. For EDOT, the Rapid ephemeris is used and as a result there is an increase in the latency that definitive orbit files are produced. EDOT is run once per day shortly after 1700 UTC and each run generates orbit files for a period of 24 hours. Because of the delay in Rapid GPS ephemeris, EDOT orbit files will have a latency of between one and two days, i.e., the earliest orbit file each run will have a latency of about 48 hours while the latest orbit file will have a latency of about 24 hours.

4.2 Reference Location

One important advantage of EDOT is that the satellite attitude is used to further resolve the position of the actual SAR antenna. Neither of the other two OD tools are capable of this. Therefore the reference position on the spacecraft for the EDOT orbit is the center of the SAR antenna. For the current definitive orbit generated by ODMP, the reference was not as well defined, but on average tended towards RADARSAT-2's center of mass, which is approximately 1 m above the center of the SAR antenna. By including the attitude in the orbit determination process, the accuracy in terms of the SAR antenna position increases because the antenna shifts position by up to one meter during attitude slews.

The approximate locations of the reference point on the spacecraft for the three different OD systems are shown in Figure 4-1. The POD reference point is near the GPS antennas, which are located on top of the satellite.

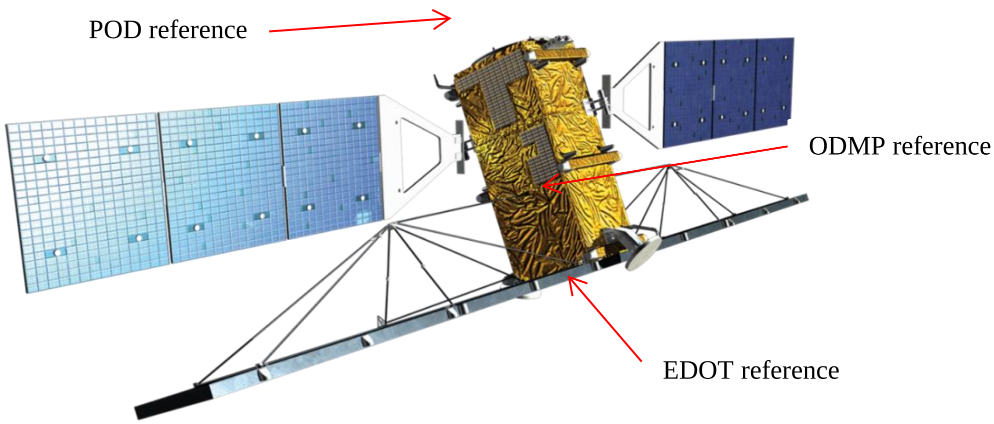

Figure 4-1 Location of reference point on the satellite for different OD systems.

4.3 Solution Uncertainty Estimation

One outcome of using the ODTK filter for orbit determination is the process itself provides an inherent estimate of the solution uncertainty. So not only does the EDOT orbit file provide the position and velocity of RADARSAT-2, it also provides a relative measure of the quality of the position and velocity. This is useful for monitoring the OD process, and also for providing users with an estimate of the solution accuracy. The uncertainty of the orbit solution for EDOT is estimated by the covariance matrix within the ODTK Kalman filter. It must be noted that this position error is not meant to be interpreted as the absolute accuracy of EDOT. The covariance estimation produced by EDOT depends on several factors internal to the OD process itself and is not absolute.

The uncertainty for position and velocity are included in the header of the new definitive orbit files. The number of lines in the header files is the same as in the current ODMP orbit files in order to minimize any impact on file readers. An example of orbit files showing the change is shown in Figure 4-2. The three values given are for the 3-σ position and velocity error estimates in the along-track, cross-track, and radial directions respectively. The units for position are meters and for velocity the units are meters per second. The update to the definitive file format is captured in the Orbit Data Services ICD, ref RK-IC-51-2336.

9	ORBIT_NUMBER = 38161
10	GPS_MODE = TRUE
11	; The following lines contain the NORAD 2-line elements:
12	; - SOM Start of Message (NOT present)
13	; - Line 1
14	; - Line 2
15	1 32382U 07061 A 15096.00000000 .00000000 00000+0 15077-2 0 1783
16	2 32382 98.5777 104.2851 0001260 92.4294 93.8740 14.29978898381506
17	; **
18	; The following state vectors are in the ECEF reference frame:
19	; Position is in meters, velocity is in meters/second
20	2015-096-17:36:14.064664
21	7912512
22	5916.72

9	ORBIT_NUMBER = 38161
10	GPS_MODE = TRUE
11	;### POS_ERR_EST: 0.477 0.295 0.114
12	;### VEL_ERR_EST: 0.000116 0.000306 0.000449
13	; The following lines contain the NORAD 2-line elements:
14	; - SOM Start of Message (NOT present), Line 1, Line 2
15	1 32382U 07061A 15096.73349612 -.00004692 00000-0 -18233-2 0 00010
16	2 32382 098.5780 105.0080 0001277 091.4682 268.6689 14.29985318381612
17	; **
18	; The following state vectors are in the ECEF reference frame:
19	; Position is in meters, velocity is in meters/second
20	2015-096-17:36:14.065
21	7912513
22	5916.717

Figure 4-2 Comparison of lines 11–14 in the old (left) and new (right) definitive orbit files.

5 TESTING AND VALIDATION

EDOT was thoroughly tested during the development and implementation stage as over seven years of orbit telemetry was reprocessed. Three different techniques were employed to assess the OD quality of EDOT. The first involves looking at the orbit determination process itself, the second is using geolocation tests, and the third is using fringe rates in InSAR interferograms.

5.1 Orbit Determination Results

The definitive orbits generated by ODMP and EDOT can be directly compared and presented in the radial, along-track and cross-track directions, as shown in Figure 5-1. In 2009, ODMP updated its gravity model and this accounts for the sharp change observed in the radial direction. There are certain events where the orbits diverged, for instance during large maneuvers or periods with large gaps in GPS telemetry, but during each divergence it was concluded that EDOT responds better than ODMP. The overall difference between the EDOT and ODMP orbits is largest in the along-track direction, where the magnitude varies between zero and 10 m.

As mentioned in the previous section, EDOT also provides its own estimate of the uncertainty in each orbit determination solution. The average uncertainty per orbit is plotted in Figure 5-2. A summary of the 1-σ and 3-σ uncertainties in the radial, along-track, and cross-track directions are included in Table 5-1. When added in quadrature the overall 3-σ position error estimate is 0.65 m ($\sqrt{0.16^2 + 0.52^2 + 0.36^2}$). It is reiterated that this is not to be interpreted as the absolute position error; however, it is a reasonable estimate of the lower bound of the error and supports the assertion that the overall orbit accuracy is better than 1 m.

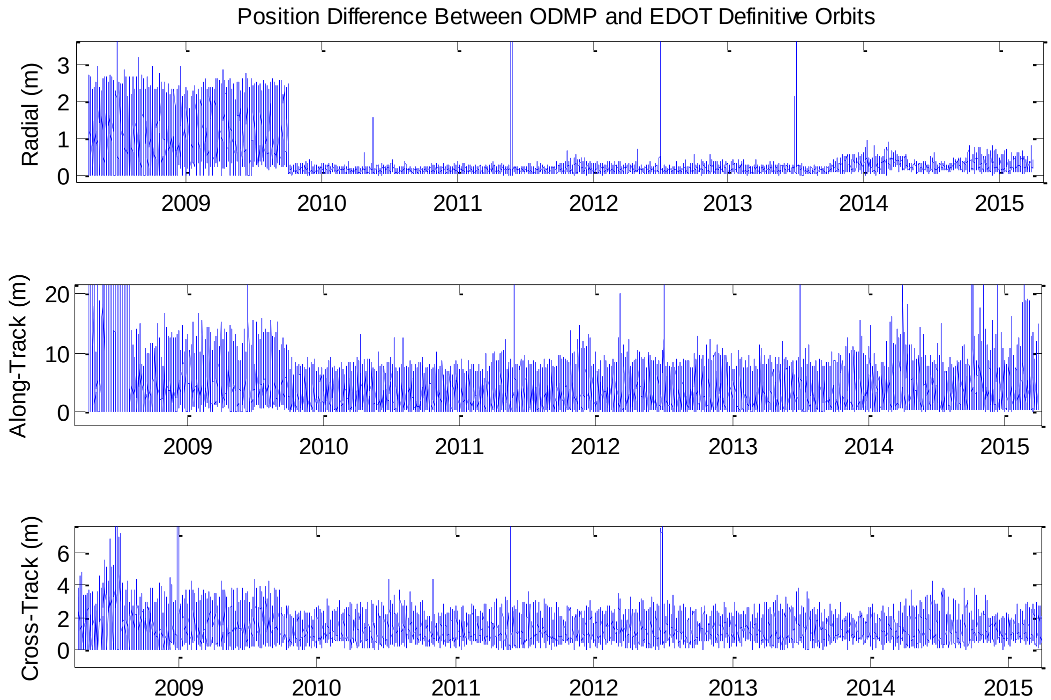

Figure 5-1 Comparison of Satellite Position Between ODMP and EDOT Definitive Orbits.

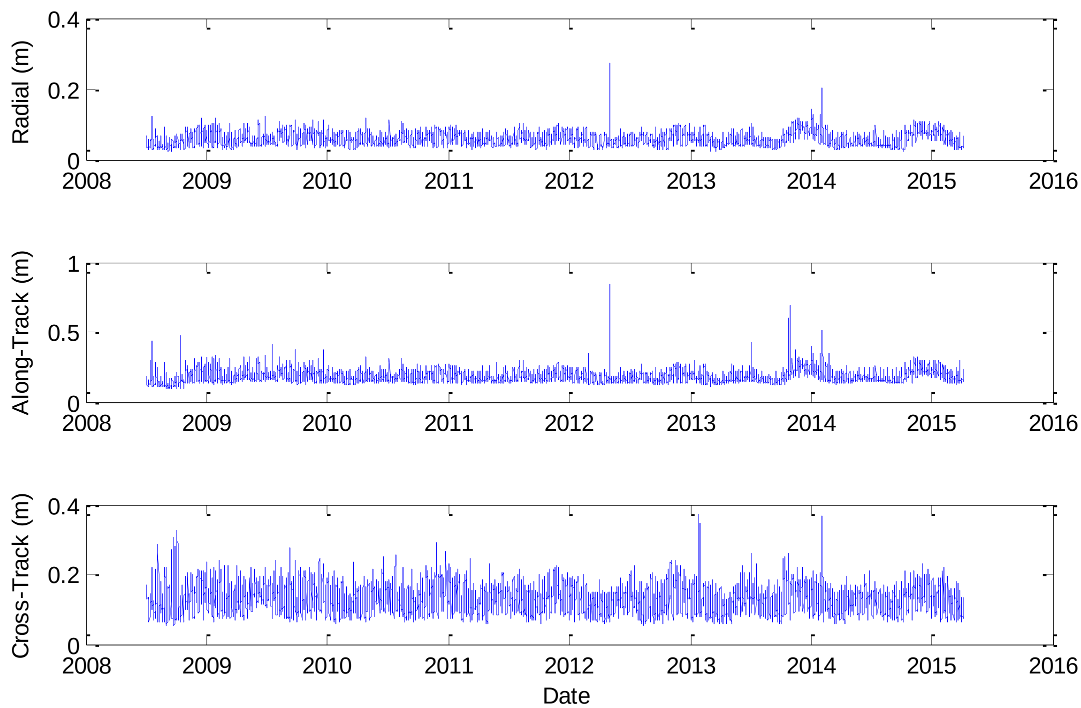

Figure 5-2 Uncertainty (1-σ) estimated for EDOT position.

Table 5-1 Summary of the EDOT Uncertainty

Direction	1-σ (m)	3-σ (m)
Radial	0.05	0.16
Along-Track	0.17	0.52
Cross-Track	0.12	0.36

5.2 Geolocation

Geolocation testing provides another measure of the orbit accuracy, albeit not a perfect one because geolocation measurements also include many other potential sources of error (e.g. payload timing, processing, ground truth knowledge, atmospheric delays) that are difficult to control. The RADARSAT-2 dataset for geolocation testing consisted of approximately two years (Fall 2010 to Fall 2012) of image quality monitoring scenes acquired in Spotlight and Ultra-Fine modes over MDA-owned calibrated trihedral corner reflectors located in Richmond, B.C., and in Quebec City (INRS), Quebec. Each location has two reflectors, one facing East that is imaged during descending right-looking passes, and the other facing West that is imaged during ascending right-looking passes.

Point target analysis of the products reprocessed with EDOT orbits was carried out on the RADARSAT-2 Image Quality Workstation. The absolute location error results were extracted, and corrections for atmospheric delays were applied to them, based on meteorological and ionosphere data obtained from the internet.

The results for the INRS East corner reflector are presented in Figure 5-3. The other three corner reflectors had similar results demonstrating that for EDOT the geolocation accuracy and precision are superior to the existing orbit data sources (Downlinked/POD and Definitive/ODMP). Overall, the RMS absolute geolocation errors observed were between 1 and 2 m depending on the site, while on exact repeat passes the standard deviations of the errors after atmospheric corrections varied from 0.2 to 0.4 m in the along-track direction, and 0.1 to 0.3 m in the slant-range direction, depending on the site and incidence angle.

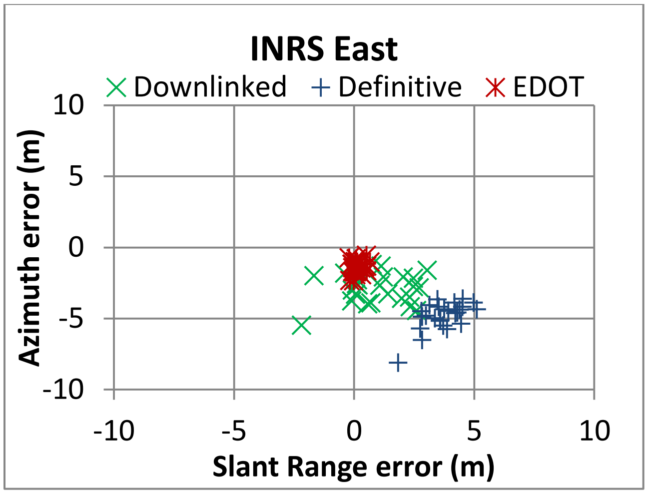

Figure 5-3 Geolocation results with INRS East corner reflector for POD (Downlinked), ODMP (Definitive), and EDOT orbit data.

5.3 InSAR

InSAR relies on accurate estimates of orbit baselines between pairs of acquisitions in order to model and remove the geometric phase component associated with the flat-earth geometry plus local topography. Relative errors in orbit position estimates cause corresponding errors in the resulting baselines and geometric phase components. The sensitivity of the phase to orbit errors provides an opportunity to estimate relative orbit errors based on the presence of residual phase ramps.

A study was performed to analyze the spatial phase distribution in a large set of RADARSAT-2 interferograms to estimate baselines and compare the difference in residual fringe rates associated with ODMP and EDOT orbit solutions. The outcome of the per-interferogram analysis is an estimate of the perpendicular and parallel baseline errors for each version of definitive orbit. The errors are then converted into ground range, azimuth and total fringe rates. The total fringe rate is computed as the root sum square of the ground range and azimuth rates. For brevity only the distribution of the total fringe-rate is shown here in Figure 5-4. The results clearly illustrate that EDOT reduces the fringe rate compared to ODMP. The total RMS (1-sigma) fringe rate for EDOT is estimated to be 0.94 fringes/100 km. A visual example of the interferogram fringe-rate improvement realized by EDOT compared to ODMP is presented in Figure 5-5.

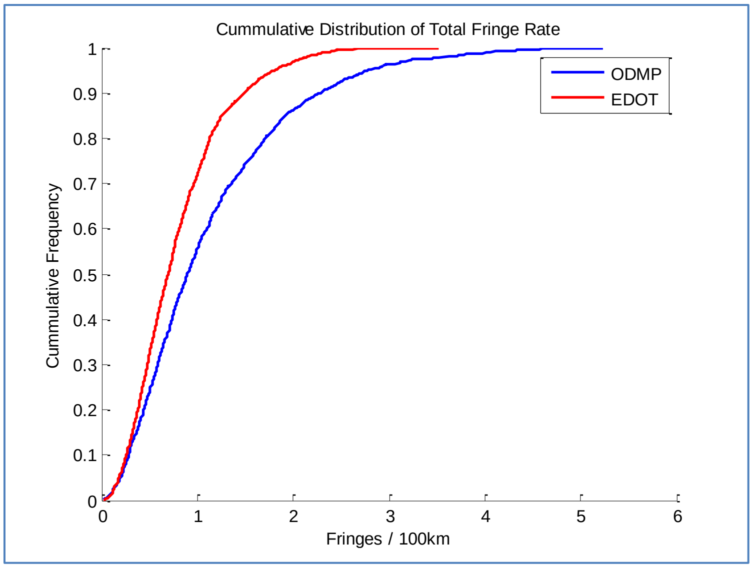

Figure 5-4 Comparison of cumulative distributions of total fringe rates for the set of F, MF and MW Wide mode interferograms.

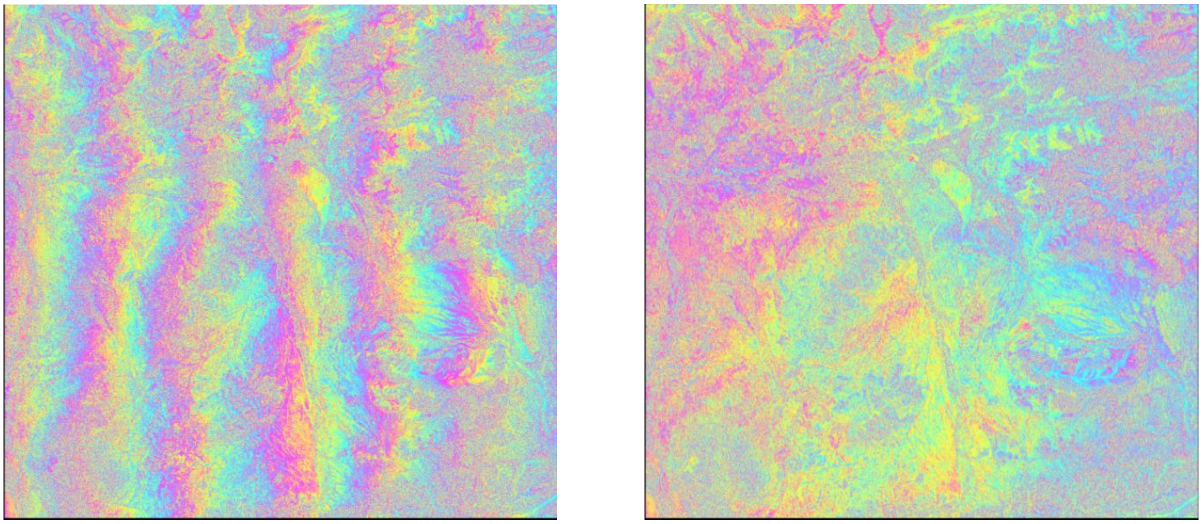

Figure 5-5 Example of interferograms processed with the ODMP definitive orbit (left) and the EDOT definitive orbit (right).

6 IMPLICATIONS FOR NETWORK STATIONS

Once the transition to EDOT orbit files is complete, the EDOT definitive orbit files will replace the current definitive orbit files. Therefore it will no longer be possible to obtain the ODMP definitive orbit files—the only definitive orbit files available will be from EDOT. Furthermore, past EDOT definitive files will be available for the entire mission so it becomes possible to reprocess and enhance previous products.

The only difference in the format of the EDOT definitive orbit file relative to the current ODMP definitive orbit file is the uncertainty values in the header, which was discussed previously. For those not wanting to use this uncertainty information, nothing will change regarding how the orbit files are used.

6.1 With Latest SAR Processor

To take full advantage of the improved accuracy of the new definitive orbit file a bias correction must be applied when processing the image with the definitive orbit. The bias correction is available in the latest SAR processor software (CAPPS SAR 1.2) and is to be enabled by forthcoming updates to the run-time environments.

6.2 Without Latest SAR Processor

For network stations that do not upgrade their processor, a patch is available from MDA as an alternative. Network stations that do not upgrade their processor or receive a patch will still have access to the EDOT definitive orbit files, but there will remain a small uncorrected bias in orbit position of about 5 m along the SAR antenna line of sight. However, this is only about 1 m larger than the bias that currently exists when processing with the old definitive orbits, so it will not have a big impact on most applications. The enhancement to the orbit accuracy is larger than 1 m so overall, using the new definitive orbit files should still offer an improvement.

6.3 Downlinked Orbit (POD)

The changes associated with the implementation of EDOT pertain only to processing with definitive orbit data. The downlinked orbit information provided by POD is not affected. No patch is required to continue to use the downlinked orbit as there is no change to the reference position of the downlinked orbit.

7 CONCLUSIONS

EDOT is a new orbit determination tool developed by MDA that complements its two existing OD tools. EDOT generates definitive orbit files that will replace the current definitive orbit files produced by ODMP. There will be an extra 24 hours of latency in the production of definitive orbit files as it is required to wait for the more accurate Rapid GPS ephemeris. The only difference to the format of the new definitive orbit is it will now contain relative uncertainty estimates in the file header. The reference point for the new definitive orbit is the SAR antenna and the latest version of the SAR processor (or a processor patch) is required to take full advantage of the enhanced orbit accuracy.

Extensive testing of EDOT was performed as new definitive orbit files were generated over the entire mission life. The results indicate that orbit accuracy improved to better than 1 m. This was demonstrated using uncertainty estimates generated during orbit determination as well as with geolocation results averaged over four different corner reflectors. A series of InSAR interferograms were analyzed to show that EDOT is capable of reducing fringe rates to under 1 fringe/100 km. Enhanced definitive orbits will be available for the entire mission so it becomes possible to reprocess earlier images to take advantage of the improved orbit accuracy.