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Observation angle and plane characterisation for ISAR imaging of LEO space objects ☆

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Abstract

For inverse synthetic aperture radar (ISAR) imaging of low Earth orbit (LEO) space objects, examining the variations in the image plane of the object over the entire visible arc period allows more direct characterisation of the variations in the object imaging. In this study, the ideal turntable model was extended to determine the observation geometry of near-circular LEO objects. Two approximations were applied to the observation model to calculate the image plane's normal and observation angles for near-circular orbit objects. One approximation treats the orbit of the space object as a standard arc relative to the Earth during the radar observation period, and the other omits the effect of the rotation of the Earth on the observations. First, the closed-form solution of the image plane normal in various attitude-stabilisation approaches was determined based on geometric models. The characteristics of the image plane and the observation angle of the near-circular orbit object were then analysed based on the common constraints of the radar line-of-sight (LOS). Subsequently, the variations in the image plane and the geometric constraints of the ISAR imaging were quantified. Based on the image plane's normal, the rotational angular velocity of the radar LOS was estimated. The cross-range direction of the ISAR image was then calibrated. Three-dimensional imaging was then reconstructed based on dual station interferometry. Finally, simulations were performed to verify the result of the three-dimensional interferometric reconstruction and to calculate the reconstruction's precision errors.
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Keywords: LEO satellite; ISAR imaging; Observation angle; Image plane; 3D imaging

1. Introduction

Inverse synthetic aperture radar (ISAR) is a valuable radar technique for assessing the dynamic state of a large object in low Earth orbit (LEO). In particular, images generated by these radars can be of sufficient resolution to be used during launch support, contingency operations or damage analysis in low Earth orbit; i.e. for confirming the deployment of structures, determining structural integrity or analysing the dynamic behaviour of an object (Lemmens et al., 2013; Rosebrock, 2011).

In ISAR imaging, the image plane lies quite different from the optical one. The line of sight (LOS) is embedded in the image plane and not orthogonal to it as in optics. The other dimension of the image plane depends on the rotational motion of the object which provides aperture angles (Walker, 1980; Chen and Andrews, 1980). In

Abbreviations: 3D, 3 dimensional; ISAR, inverse synthetic aperture radar; LEO, low Earth orbit; LOS, line-of-sight; R-D algorithm, range-Doppler algorithm

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general, the set of LOS vectors at different times in the object-fixed coordinate system spans a surface. Usually, this surface can be approximated by a plane which can then be identified as the image plane. This is especially the case for comparatively small angles between the LOS vectors at different times, corresponding to a small time interval.

For space objects, studying the variations in the image plane over the entire visible arc can provide a more direct view of the variations in the object imaging. For the majority of imaging scenarios, including the imaging of a space object, the radar and the object's orbit do not share the same plane, and the motion of the object is restricted to its orbit, which is inconsistent with the assumption of uniform linear motion with a constant velocity. In addition, several types of space objects are subject to stabilisation controls by many types of attitudes, which prevent the acquisition of the rotation angle from translational motion alone. Under these circumstances, it is necessary to expand the turntable model and analyse the ISAR imaging model. Fig. 1(a) and (b) illustrate the ideal turntable model and the ISAR image planes for a space object. The image plane normal of the space object model is no longer perpendicular to the motion plane of the object. In addition, the change in the image plane, which is the same as the two-dimensional projection plane determined by the range direction and the cross-range detection, will affect various imaging algorithms (Dong et al., 2009).

This study discusses two attitude-stabilisation approaches for space objects and establishes the geometry of LEO space object imaging. Based on geometric observations, the closed-form solution of the image plane normal is derived. The changes in the image planes and observation angles are then analysed. Based on the image plane normal, the rotational angular velocity of the radar LOS is estimated. The cross-range direction of ISAR image is then calibrated using the cumulative rotation angle. In this way, a 3D image is reconstructed based on dual-station interferometry. Finally, simulations are performed to verify the 3D interferometric reconstruction result and to obtain the reconstruction's precision errors.

2. Observation geometry of ISAR imaging of LEO space objects

2.1. Definitions of the coordinate systems

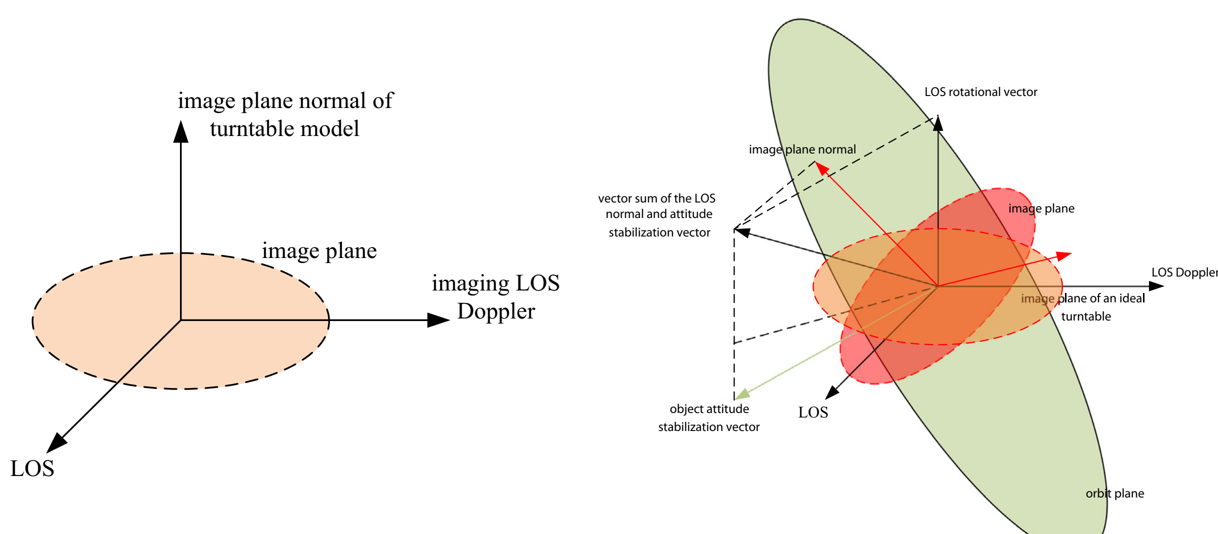
Although many satellite-based systems exist, much of the nomenclature isn't standard, and many systems are developed for specific satellite missions. Each of these systems is based on the plane of the satellite's orbit (Vallado, 2001). In this study, four coordinate systems will be used in the subsequent analysis, including the reference orbit coordinate system, satellite-based coordinate system, object-fixed coordinate system and reference radar coordinate system as shown in Fig. 2.

2.1.1. Reference orbit coordinate system

The reference orbit coordinate system in Fig. 2 is marked in dark blue lines. The orbital plane is set as the XY plane. The centre of the Earth O is the origin. The X-axis is along the direction of OD, and the positive direction of the Y-axis is perpendicular to the X-axis in the direction of the velocity at point D. The Z-axis is defined according to the right-hand rule. In this study, we assume that the reference orbit coordinate system is equal to the inertial coordinate system.

2.1.2. Satellite-based coordinate system

The satellite-based coordinate system in Fig. 2 is marked in blue lines. The orbit plane is set as the xy plane.



(a) (b)

Fig. 1. An ideal turntable and the image plane normal of a space object. (a) The image plane and its normal axes in an ideal turntable model. (b) Illustration of the image plane and its normal for a space object.

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