Semantic Space Modeling of Ocean Environments Using a CityGML-Based Approach

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This study proposes a semantic modeling approach for representing ocean spaces by extending CityGML 3.0 through integration with IHO's S-100 specifications. Ocean environments differ fundamentally from their terrestrial counterparts in that they exhibit a scarcity of physical features, complex jurisdictional boundaries, and dynamic three-dimensional spatial structures. These characteristics necessitate a shift from traditional feature-centric modeling to a space-centric paradigm. Drawing on experience in geospatial standardization and practical limitations encountered in separating geometry from semantics, this work introduces a prototype "OceanGML" framework.

This framework reuses the core structure of CityGML while incorporating ocean-specific modules such as OceanTopography, OceanLinkBoundary, OceanTransportation, and OceanLife. The model allows multi-perspective interpretation of identical ocean volumes-legal, economic, ecological-and supports volumetric representations based on S-100 Part 8 gridded data. This approach aims to bridge the semantic interoperability gap across stakeholders and enhance the foundational architecture for ocean digital twins.

To adequately capture the spatiotemporal and semantic complexity of marine spaces, a new modeling approach is required-one that transcends the constraints of land-based paradigms grounded in discrete, feature-centric entities. Oceans instead comprise expansive, visually sparse yet semantically rich volumes, where spatial meaning emerges from fluid dynamics, legal interpretations, and ecological processes. Addressing these conditions, the proposed framework offers a semantically enriched structure for marine digital twins, aligned with CityGML 3.0 and S-100 specifications.

Table 1 Comparison of Semantic Modeling Approaches between Land and Ocean Domains

Element	Feature-Centric Approach (Land)	Space-Centric Approach (Ocean)
Modeling Unit	Physical objects (e.g., buildings, roads, parcels)	Volumetric space blocks or marine regions (e.g., sea layers, zones)
Semantic Focus	Object → Attribute → Activity	Space → Condition → Event
Representation Style	Structured classes (e.g., Building → Function)	Spatial partitioning with temporal attributes
Data Structure	Discrete features with defined boundaries	Continuous 3D volumes with dynamic conditions
+Expression Method	Hierarchical object classes with attributes	Spatiotemporal field + semantic annotation (e.g., current, temperature)
Applications	Urban planning, facility management, infrastructure	Marine spatial planning, environmental modeling, ocean digital twin

Unlike terrestrial domains that rely on discrete, feature-based representations, marine environments demand a space-centric modeling paradigm capable of accommodating temporal variability, vertical stratification, and jurisdictional ambiguity. Dominated by dynamic phenomena-including sea surface fluctuations, subsurface currents, and evolving seafloor topography-these spaces require time-sensitive, three-dimensional representations. These characteristics underscore the need for semantic-based modeling as a foundation for constructing interoperable digital twins. Such models must also accommodate diverse stakeholder interpretations of identical spatial units, in alignment with the mission space concept, which defines context-specific objectives, responsibilities, and operational semantics in marine domains.

In response, this study presents a semantic modeling framework that supports multi-perspective interpretations of ocean spaces within digital twin environments. Leveraging the modular architecture of CityGML 3.0-including components such as Appearance, Versioning, Dynamizer, and PointCloud-this framework introduces an Application Domain Extension (ADE) named OceanGML. OceanGML integrates key S-100 product specifications and enables semantic layering that reflects distinct stakeholder perspectives. This standards-based yet extensible approach addresses the longstanding modeling gap between land and sea. As shown in Figure 1, existing CityGML modules are expanded through a set of ocean-specific domain modules, each semantically aligned with corresponding S-100 standards. These modules include:

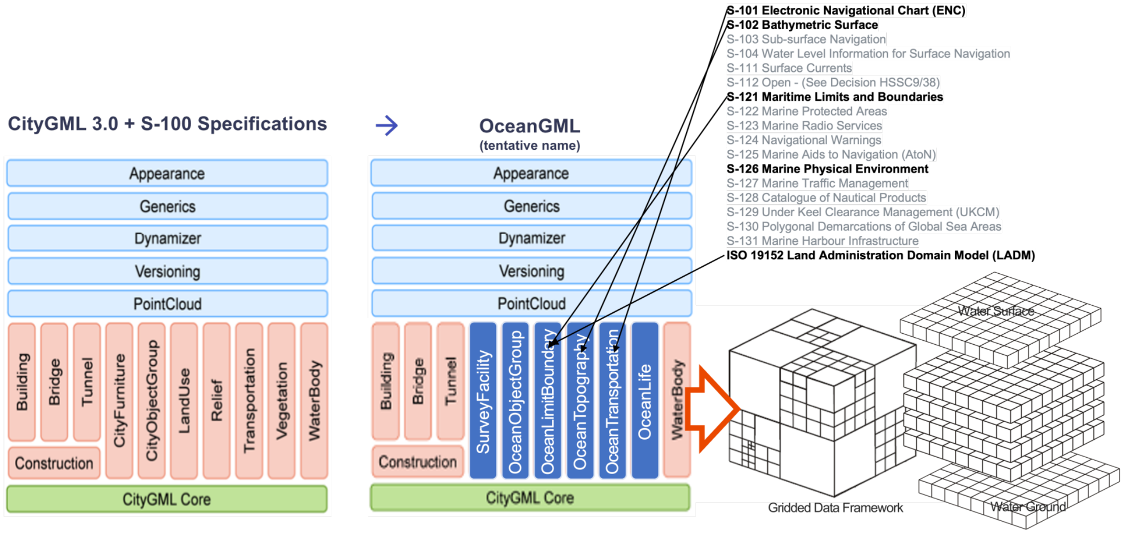

Figure 1 Architecture of OceanGML integrating the CityGML Modules and the S-100 Standards

- OceanTopography: for 3D bathymetric and volumetric grid representations
- OceanLinkBoundary: for legal and functional demarcations (e.g., EEZ, protected zones)
- OceanTransportation: capturing currents, traffic corridors, and navigational constraints
- OceanLife: representing biological or ecological designations (e.g., MPAs)
- OceanObjectGroup: grouping physical and abstract marine entities

The model is semantically aligned with key S-100 product specifications such as S-101, S-102, S-104, S-121, and S-126. It also adopts the S-100 Part 8 Riemann grid framework to enable structured 3D volumetric representation. This configuration allows the same oceanic space to be semantically differentiated by stakeholder roles-for example, jurisdictional boundaries for governments, navigational corridors for industry, ecological reserves for conservationists, or mission zones for military use. Through multi-perspective annotation and contextual ontology layering, OceanGML facilitates pluralistic spatial semantics and mitigates the long-standing fragmentation in marine spatial data. As a result, it enhances interoperability and fosters integrated, stakeholder-informed decision-making.

Table 2 Key Perspectives on Applying CityGML to Marine Semantic Modeling

Perspective	Description
Separation of Geometry and Semantics	CityGML distinctly separates spatial geometry from semantic information, making it well-suited for modeling marine environments where physical space and contextual meaning often evolve independently.
Extensibility via ADE Mechanism	CityGML supports Application Domain Extensions (ADE), allowing the definition of marine-specific classes that align with ocean domain semantics without altering the core schema.
3D Volumetric and Temporal Modeling	CityGML 3.0 supports volumetric representations and dynamic, time-dependent features through modules like Dynamizer, enabling representation of marine volumes and temporal variations (e.g., tides, currents).
Multi-Perspective Semantic Layering	The same ocean region can be assigned multiple semantic layers reflecting stakeholder-specific views (e.g., jurisdiction, fisheries, conservation), enabling flexible modeling of mission-specific marine contexts.

A prototype implementation of OceanGML demonstrates that the framework can effectively represent volumetric ocean regions with stakeholder-specific semantic layers, aligning CityGML structures with key S-100 product specifications. This capability addresses persistent interoperability challenges in marine spatial planning and supports mission-oriented digital twin applications. Ongoing work focuses on formalizing the OceanGML ADE schema and validating its applicability in operational contexts. With its modular design and standards-based architecture, OceanGML contributes a foundational step toward an internationally harmonized semantic framework for marine digital twins.