Observation of tidal loading effects on cosmic-ray muons in a submarine environment

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Abstract

Abstract: In water-covered environments, temporal variations in muon flux are influenced not only by subsurface density structures but also by mass loading associated with changes in the overlying water column. Ocean tides induce periodic variations in water mass, which can significantly modulate the observed muon flux. To quantify this effect, a muon detection system installed inside a subsea tunnel in the Xiamen area was operated continuously for approximately eight days. After correcting for atmospheric pressure and weighted effective temperature effects, a clear periodic signal synchronous with tidal height variations was identified in the muon flux time series. Spectral analysis shows that both the corrected muon flux and tidal height exhibit a pronounced periodic peak at approximately 12.85 h. Correlation analysis further indicates a strong negative correlation between the two signals, with a correlation coefficient of -0.796 and a minimum lag of approximately 1 h, demonstrating that tidal-induced water mass loading constitutes a first-order physical mechanism controlling muon flux variations in this setting. Based on this interpretation, tidal effects were removed prior to two-dimensional density imaging. The corrected results show that the path-averaged density distribution remains stable over time and reveals high-density anomalies in specific azimuthal directions that are consistent with independent geological information. These results demonstrate that accurate identification and correction of tidal loading effects are essential for reliable muon imaging in water-covered environments, and they provide a necessary physical basis for subsea and nearshore geophysical applications.

Full Text

Preamble

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Abstract

water-covered environments, temporal variations influenced subsurface density structures loading associated changes overlying water column.

Ocean tides induce periodic variations water mass, which significantly modulate observed flux. quantify effect, detection system installed inside subsea tunnel Xiamen operated continuously approximately eight days.

After correcting atmospheric pressure weighted effective temperature effects, clear periodic signal synchronous tidal height variations identified series.

Spectral

analysis

shows corrected tidal height exhibit pronounced periodic approximately Correlation

analysis

further indicates strong negative correlation between signals, correlation coefficient minimum approximately demon strating tidal-induced water loading constitutes first-order physical mechanism controlling variations setting.

Based interpretation, tidal effects removed prior two-dimensional density imaging. corrected

results

path-averaged density distribution remains stable reveals high-density anomalies specific azimuthal directions consistent independent geological information.

These

results

demonstrate accurate identification correction tidal loading effects essential reliable imaging water-covered environments, provide necessary physical basis subsea nearshore geophysical applications.

Keywords

imaging; Subsea observation; Geological structure; Tidal loading; modulation; Density inversion

1. Introduction

Cosmic-ray muography passive non-destructive imaging technique exploits energy scattering characteristics high-energy cosmic-ray muons propagate through matter Because attenuation highly sensitive path-integrated density along trajectory, detected intensity primarily controlled equivalent overburdened materials Owing physical principle, muography increasingly applied range geophysical investigations, including volcanic structure imaging detection underground cavities fault-zone characterization engineering geological surveys Compared conventional geophysical methods, muography require active sources enables long-term, continuous observations complex environments, providing unique means quantitative inversion subsurface density structures. environments covered water bodies, oceans, lakes, underwater engineering settings, muographic observations subject additional physical complexities Variations water levels between seasons, groundwater table fluctuations hydrological processes, astronomical ocean tides temporal changes water thickness above target region.

These variations modify cumulative loading along trajectories consequently induce systematic modulation observed flux. subsea settings particular, tidal-induced water variations occur scales comparable those observations superimposed signals associated subsurface density structures, thereby degrading resolving power muographic imaging [13].

Accurate identification quantitative assessment water-induced loading effects therefore essential prerequisites achieving high-precision muography water-covered environments.

Among various hydrological oceanographic processes, astronomical tides dominant controlling short-term, quasi-periodic sea-level variations marine environments.

Tidal loading induces predictable changes overlying water column mass, which directly modulate semi-diurnal diurnal scales. contrast subsurface density structures, which generally exhibit quasi-static behavior observation periods, tidal loading characterized strong periodicity predictability. theoretical perspective, periodic mass-loading effects should manifest separable signals

long-term series [14,15] However, owing observational geometry constraints practical complexity deploying detectors marine environments, direct experimental investigations tidal effects remain limited.

Existing studies largely relied numerical modeling qualitative discussions, while systematic field-based validation tidal signal detectability, amplitude characteristics, their quantitative muographic correction still lacking. study, conducted direct observational investigation tidal loading effects using detection system installed inside subsea tunnel.

Continuous measurements performed total duration providing opportunity examine response ocean tidal variations under controlled geometric conditions. systematically correcting known atmospheric influences, including barometric pressure weighted effective atmospheric temperature, periodic variations synchronous astronomical tidal height extracted series. relationship between tidal loading quantitatively evaluated, revealing significant negative correlation between signals.

Furthermore, tidal loading effects removed prior density reconstruction, two-dimensional muographic imaging subsequently performed using corrected dataset. resulting density images exhibit temporally stable path-averaged density distributions reveal high-density anomalies consistent independent geological information.

These

results

demonstrate tidal loading critical physical factor accounted muography under water-covered conditions, represents natural time-dependent modulation source exploited correction physical interpretation. study therefore provides important experimental basis application muography subsea engineering nearshore geophysical investigations

2.1 Principles

imaging Primary cosmic interact atomic nuclei Earth atmosphere produce secondary particles, among which dominant.

These pions subsequently decay muons, which constitute component cosmic-ray muons reaching Earth surface. production atmospheric muons mainly occurs altitudes approximately

above level. dominant decay processes expressed where denote muons represent (anti-)neutrinos.

Muons propagate downward through atmosphere, level approximately energy about muons traverse matter, their energy dominated ionization processes, while high-energy muons radiative losses contribute. average energy expressed

= + # 2

where represents ionization denotes radiative term. given incident direction residual capable penetrating thickness related minimum energy

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where denotes thickness material, expressed units represents length within object; denotes density distribution material along path. minimum penetration energy residual ratio given where denotes energy spectrum. measuring before after transmission through medium different directions residual ratio calculated, allowing inversion path-averaged density density anomaly distribution overburden above detector

2.2 Correction

environmental effects influenced structure overburdened materials variations atmospheric environment [17,18] expressed

where represent variations induced atmospheric pressure effects atmospheric temperature effects, respectively.

Prior investigating modulation tidal loading, necessary first remove influences atmospheric pressure atmospheric temperature. influence atmospheric pressure represented using linear model

=

where denotes flux, represents atmospheric pressure, barometric coefficient. denote deviations atmospheric pressure their respective values. temperature effect described using atmospheric weighted temperature which integrates atmospheric temperature production layer level accounts entire process production propagation surface. influence atmospheric weighted temperature expressed

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=

=0 = − − 1

where denotes temperature coefficient represents relative variation atmospheric weighted temperature.

Here, denotes atmospheric depth given altitude, atmospheric temperature altitude represents ground-level altitude. coefficients estimated through linear regression.

After applying above corrections, corrected obtained.

analysis

between tidal signal After applying atmospheric corrections, relationship between corrected ocean tides further examined.

Variations sea-level tidal height equivalently

converted variations thickness overlying water column.

Under first-order approximation, influence mass-thickness variations considered linear.

Accordingly, relative variation expressed

$= \quad \text{tide } \Delta \quad - \quad \#\ 11$

where denotes tidal response coefficient represents Owing pronounced periodicity ocean tides, periodic component expected present signal.

Spectral

analysis

therefore performed corrected tidal height variation, which distinct spectral peaks theoretically anticipated. addition, Pearson correlation coefficient between calculated. time-lag

analysis

further introduced quantitatively evaluate modulation characteristics tidal loading flux.

2.4 Tidal

signal removal density imaging After confirming stable correlation between corrected tidal height variations, tidal loading regarded separable component series. isolate component, spectral

analysis

first performed atmospherically corrected frequency domain. dominant tidal periodicity (approximately identified removed. filtered signal transformed domain obtain tidal effects suppressed.

Because atmospheric effects tidal loading modify total overburden above detector, their influence angular distribution assumed isotropic first order.

Accordingly, proportional corrections applied uniformly two-dimensional angular distribution data.

Using hourly tidal-corrected angular distributions, two-dimensional density imaging subsequently performed. corrected accumulated daily intervals improve

statistical stability. comparing reconstructed density distributions different times, path-averaged density structure above detector spatiotemporal variation characteristics evaluated.

3.1 Experimental

detector deployment

experiment

conducted inside cross-sea subsea tunnel connecting District

Xiang District offshore Xiamen, Fujian Province, China. detector installed within structurally stable bedrock section tunnel, located fully enclosed underground environment. overburden above detector consists primarily tunnel structural layers, seawater column, overlying seabed sediments bedrock. detector field mainly oriented toward zenith direction, enabling detection cosmic-ray muons after transmission through overlying materials. geographic location observation shown coordinates detector longitude latitude. directly overlain seawater.

During observation period, surrounding environment remained stable, significant construction activities structural disturbances.

Anthropogenic influences measured therefore considered negligible, making suited investigating tidal modulation effects flux. presents available geological survey above observation point. overburden directly above detector comprises approximately seawater, soil, bedrock. indicates interface. layer mainly consists marine sediments completely weathered granite, whereas layer composed predominantly slightly weathered fresh granite.

Geographic location Xiamen subsea tunnel. Based engineering design drawings available geological survey data, simplified structural model overburden above observation point constructed physical

simulation. model incorporates tunnel structural layers, overlying seawater column, bedrock units beneath seabed.

Representative density values assigned material according geological information. transport through geological model simulated using Geant4. incident source generated providing realistic cosmic-ray spectra surface. simulations yielded expected angular distribution total counts under assumed structural configuration.

Geological profile above observation point derived prior investigation. overburden comprises seawater, sedimentary deposits, underlying bedrock.

3.2 Tidal

meteorological sources Xiamen region located along southeastern coast China influenced astronomical tides western Pacific Ocean. tidal regime characterized predominantly semi-diurnal tides.

Tidal height obtained National Marine Science Center China, temporal resolution consistent sampling interval data. tidal range during observation period reached dominant period approximately typical semi-diurnal tidal systems.

Variations tidal height directly induce temporal changes thickness loading overlying seawater column above detector, providing favorable conditions investigating tidal modulation effects flux. variations influenced atmospheric pressure temperature.

Surface atmospheric pressure temperature during observation period collected correction purposes. atmospheric conditions shown where presents barometric pressure shows atmospheric weighted temperature pressure obtained nearby ground-based meteorological station, which effectively represents variations lower atmospheric column above detector.

Atmospheric

temperature profiles retrieved open-access platform Open-Meteo covering altitudes surface approximately Based relative contributions different atmospheric layers parent particle production decay, temperature profile vertically weighted integrated derive time-dependent atmospheric weighted temperature Meteorological variables data. solid indicates flux.

Atmospheric pressure representing variations near-surface atmospheric mass.

Effective atmospheric temperature derived weighted temperature profile atmospheric column

experiment

employed detector based plastic scintillators, consisting multiple detection layers. maximum detection range covers zenith angles azimuth angles observation period extended November November 2025, sampling interval total effective continuous acquisition exceeding dominant astronomical tidal period Xiamen region.

Prior subsea tunnel experiment, open-sky

background

measurements conducted surface characterize reference flux. presents two-dimensional angular distribution muons. shows simulated distribution under open-sky conditions, while Compared open-sky case, observed within tunnel sig-

nificantly reduced, reflecting attenuation effect overlying materials transmitted muons.

Comparison count rates under different overburden conditions. under open-sky conditions. inside tunnel, showing attenuation overlying materials. investigate temporal variations flux, series count during observation period further analyzed, shown 5(a), solid represents measured count rate. clear semi-diurnal periodic variation observed, indicating that, beyond statistical fluctuations, contains significant environmental modulation component. dashed denotes simulated count tidal height whereas dashed represents simulated count tidal height observed count rates within range bounded these simulated values, suggesting measured variations physically consistent expected attenuation induced tidal changes overlying water column. shows numerically simulated count rate. simulation performed using three-dimensional geological model constructed longitudinal section observation horizontally extrapolated north south direction.

Topographic geological variations along direction explicitly incorporated. simplified assumption introduce discrepancies between simulated observed values.

Therefore, simulation

results

intended primarily order-of-magnitude trend comparison, providing supportive insight attenuation effect overburden rather strict quantitative match.

Comparison between observed simulated rates domain. series. dashed lines represent reference count rates different tidal heights, dashed dashed Simulated based geological model.

4.1 Influence

Meteorological Factors illustrates influence meteorological factors variations. shows relationship between relative variation atmospheric pressure. negative correlation observed: atmospheric pressure increases, total atmospheric above detector increases, leading reduction flux. linear regression applied quantify relationship, yielding barometric coefficient value consistent expected attenuation effect increased atmospheric overburden secondary cosmic-ray muons presents relationship between relative variation variation atmospheric effective temperature. correlation exhibit statistical significance. possible explanations considered.

First, strong absorption low-energy muons overlying seawater layers, detected muons predominantly high-energy spectrum, which sensitive atmospheric temperature variations.

Second, equivalent variation associated atmospheric temperature changes relatively small. short observational timescales, subtle effect difficult distinguish statistical fluctuations.

After applying pressure correction using derived barometric coefficient, pressure-corrected series obtained, shown curve represents count rate, while orange curve shows corrected count rate.

Compared original data, corrected series exhibits pronounced periodic fluctuations during latter observation period.

During interval, astronomical

tidal signal evident, indicating pressure correction effectively suppresses atmospheric interference provides basis subsequent tidal signal analysis.

Linear correlation between meteorological variations count rate.

Atmospheric pressure Effective atmospheric temperature count rates before after meteorological corrections. solid shows uncorrected data, orange solid shows corrected data, illustrating effect atmospheric correction.

Analysis

further investigate possible tidal modulation embedded flux, spectral analyses performed pressure-corrected series tidal height series.

results

shown shows tidal height spectrum exhibits prominent period approximately dominant semi-diurnal tidal component. power spectrum reveals clear period. coincidence indicates contains periodic component

synchronized with tidal variations. 294

isolate semi-diurnal component, signals normalized band-pass filtered within range effectively suppressing higher- lower-frequency contributions. filtered normalized signals shown 9(a). clear periodic behavior observed series, evident anti-phase relationship between tidal height flux. cross-correlation

analysis

presented 9(b). maximum correlation coefficient reaches 0.796, demonstrating strong negative correlation between signals. correlation occurs tidal signal leads signal approximately attributed several factors, including spatial separation between tidal gauge station water column directly above detector, dynamic response local tidal loading, minimum sampling interval measurements.

Considering these uncertainties, observed remains within physically reasonable range affect identification tidal modulation series tidal height corrected flux, together their spectral analyses.

Tidal height; corrected flux; power spectrum tidal signal; power spectrum flux.

Cross-correlation phase

analysis

dominant periodic components. Time-domain cross-correlation function; phase difference between signals.

4.3 Tidal

Correction Density Imaging Using tidal height physically constrained variable, regression relationship between tidal loading established domain. separability tidal component further verified frequency domain. two-dimensional density imaging

results

derived corrected time-domain regression, while frequency-domain filtering

results

consistency validation. applied series spectral analysis. band-stop filter implemented remove tidal-related frequency components within period range, thereby suppressing semi-diurnal tidal contribution variations. compares series spectra before after tidal correction.

After filtering, dominant periodic component associated semi-diurnal significantly reduced power spectrum. domain, systematic modulation induced tidal loading effectively suppressed, indicating tidal signal separable underlying variations.

These

results

demonstrate tidal loading deterministic modulation component subsea observations quantitatively mitigated. correction improves stability baseline enhances reliability subsequent density inversion imaging analyses.

Comparison signals before after tidal filtering. series before after filtering, filtered signal shown orange; power spectra before after filtering.

Distribution average density length during observation period. enhanced density feature observed azimuth range consistent granite structure indicated geological Using tidal-corrected data, two-dimensional density imaging inversion performed. presents cumulative average density distribution obtained observation period.

Peripheral regions insufficient statistics correspondingly large uncertainties excluded interpretation. relatively higher average density observed within zenith angle range specific azimuthal directions. spatial orientation high-density region

consistent protruding granite indicated geological survey shown Moreover, distribution exhibits clear right asymmetry. side, granite occupies larger proportion propagation length, resulting higher effective integrated density along direction. contrast, region behind observation point corresponds decreasing seabed elevation, where overburden thickness reduced.

Consequently, inferred average density

direction comparatively lower. Average density length distributions obtained consecutive two-day intervals.

November; November; November. Overall, spatial density pattern derived imaging agrees known geological structure, supporting validity tidal correction procedure reliability subsea muon-based density reconstruction.

Analysis

of Tidal Modulation 359

Under subsea nearshore observational conditions, tidal sea-level variations equivalently interpreted periodic changes water above detector.

Compared atmospheric pressure temperature effects, tidal loading characterized larger amplitude highly stable periodicity. equivalent variation reach magnitude sufficient induce significant modulation short observational times cales. study, strong negative correlation between tidal height observed subsea tunnel environment, indicating tidal loading constitutes first-order systematic effect imaging under conditions.

result

implies that, environments substantial water overburden, temporal variations originate subsurface structural changes. considerable fraction observed signal attributed dynamic variations overlying water thickness. unrecognized uncorrected, tidal modulation overlap genuine density anomaly signals comparable timescales, thereby affecting reliability imaging

results

nearshore regions, subsea tunnels typically buried depths Large astronomical tides induce sea-level variations approximately producing clearly observable modulation flux. present measurements, maximum observed variation reached approximately counts hour, about total

count rate. contrast, equivalent loading associated atmospheric temperature variations generally smaller magnitude. short observation periods, modulation effect comparatively weak.

Under subsea tunnel conditions, strong absorption low-energy muons overlying water further enhances sensitivity detected changes total loading. result, tidal modulation becomes statistically dominant observed variations.

5.2 Impact

Tidal Correction Two-Dimensional Density Imaging spectral

analysis

performed study demonstrates dominant frequency component coincides tidal height, strong negative correlation coefficient correlation indicates tidal loading introduces deterministic temporal component observed flux. tidal loading accounted time-dependent variations introduce systematic biases associated observation period. biases reduce comparability statistics across different directional bins, particularly different tidal phases unevenly sampled. result, density inversion inadvertently incorporate temporal modulation effects spatial reconstruction. treating tidal modulation separable temporal component applying correction, periodic interference series effectively reduced. enables imaging

analysis

focus primarily spatial variations attenuation rather temporal fluctuations induced external loading.

results

further that, after tidal correction, high-density directions identified two-dimensional path-averaged density distribution remain consistent across different observation days. improved temporal stability indicates tidal correction enhances robustness imaging under subsea conditions. stability particularly important long-term monitoring multi-period subsea muography applications, where consistent baseline conditions essential reliable interpretation.

6. Conclusions

Based approximately eight continuous observations conducted inside subsea tunnel Xiamen, study systematically investigated modulation effect tidal loading under water-covered conditions evaluated impact

two-dimensional density imaging. After applying atmospheric pressure effective temperature corrections, pronounced periodic component remained series.

Spectral

analysis

revealed tidal height exhibit dominant peaks period approximately principal semi-diurnal tidal constituent.

Correlation

analysis

further demonstrated strong negative relationship between relative variation tidal height, correlation coefficient minimum approximately These

results

indicate variations water-column induced ocean tides constitute first-order physical mechanism modulating subsea environments. treating tidal signal separable temporal component applying appropriate correction, periodic interference series effectively reduced. two-dimensional path-averaged density distribution derived corrected exhibits improved temporal stability reveals persistent high-density feature azimuth approximately consistent orientation granite indicated regional geological surveys.

Overall, study demonstrates that, environments significant water overburden, accurate identification correction tidal loading effects essential high-precision imaging.

results

provide critical physical constraint application muography subsea engineering nearshore geophysical investigations.

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Figure 1

Figure 1: Figure 1

Abstract

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