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水库大坝运行风险遥感监测技术探索

Exploration of Remote Sensing Monitoring Techniques for Reservoir Dams Operation Risk

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汇报提纲 Outline

Part 1

水利工程遥感监测应用现状

Current Status of Remote Sensing Monitoring Applications in Hydraulic Engineering

安全监测发展历程 Development History of Safety Monitoring

- 水库大坝安全监测发展历经四个阶段，管理水平不断提高，智能化应用不断增强，溃坝及事故概率大幅降低

Dam safety monitoring has gone through four stages, with management levels continuously improving and dam failures significant reduction

Phase 4 **智慧化**·透彻感知、自我学习、精准预知、决策支持
Wisdom

Phase 3 **智能化**·信息感知、存储、分析应用
Intelligence

Phase 2 **自动化**·采集数据及其基本应用
Automation

Phase 1 **人工化**·表观巡查、人工观测记录分析
Manual

需求持续升级

Demand continues to rise

人工 → 自动

粗放 → 精细

信息化 → 智慧化

当前和未来：如何利用现代信息技术手段全面保障安全

How to comprehensively ensure dam safety with information technology in the future?

发展趋势 Development Trend

- 传统地面监测：费时费力，建设和运行维护成本高，测点数量有限，时效性和全面性难以满足

Ground monitoring: High construction and operation maintenance costs, limited number of measurement points, and difficulty in meeting timeliness and comprehensiveness

- 卫星遥感监测：可持续获得大范围影像监测数据，全面感知工程态势变化，弥补地面监测不足，是实现水库大坝现代化管理（数字孪生水利工程、水库运管矩阵）的重要技术支撑和保障

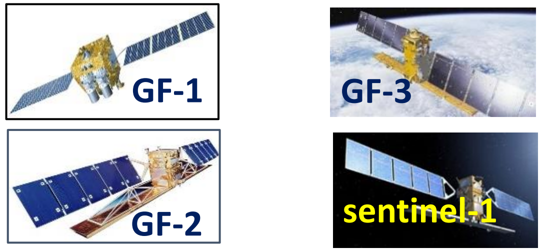
Satellite remote sensing monitoring: sustainably obtain large-scale image monitoring data, comprehensively perceive changes in engineering trends, can compensate for insufficient ground monitoring

传统地面监测 Ground Monitoring

变形、渗流、应力应变等

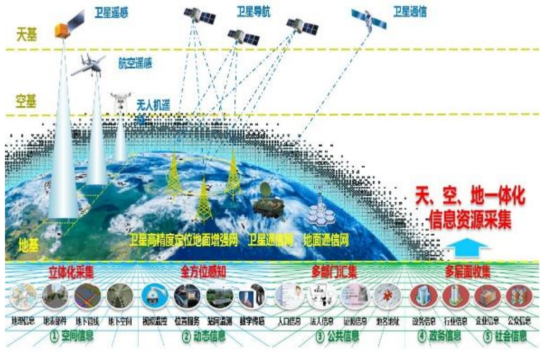
卫星遥感监测 RS Monitoring

高分卫星、测高卫星、
SAR卫星、重力卫星等



多尺度监测 Multiscale Monitoring

卫星+航空+地面
多源监测数据融合



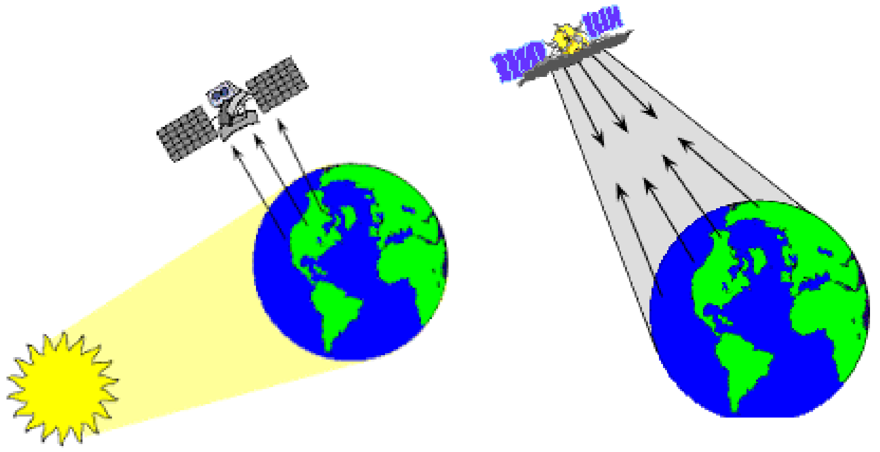
- **风险全要素掌握（上下游、左右岸）**

Mastering all elements of risk (upstream and downstream, left and right banks)

- **全天候动态管控（枢纽区、库区、下游河道）**

All-weather dynamic control (hub area, reservoir area, downstream river channel)

卫星遥感 Satellite Remote Sensing



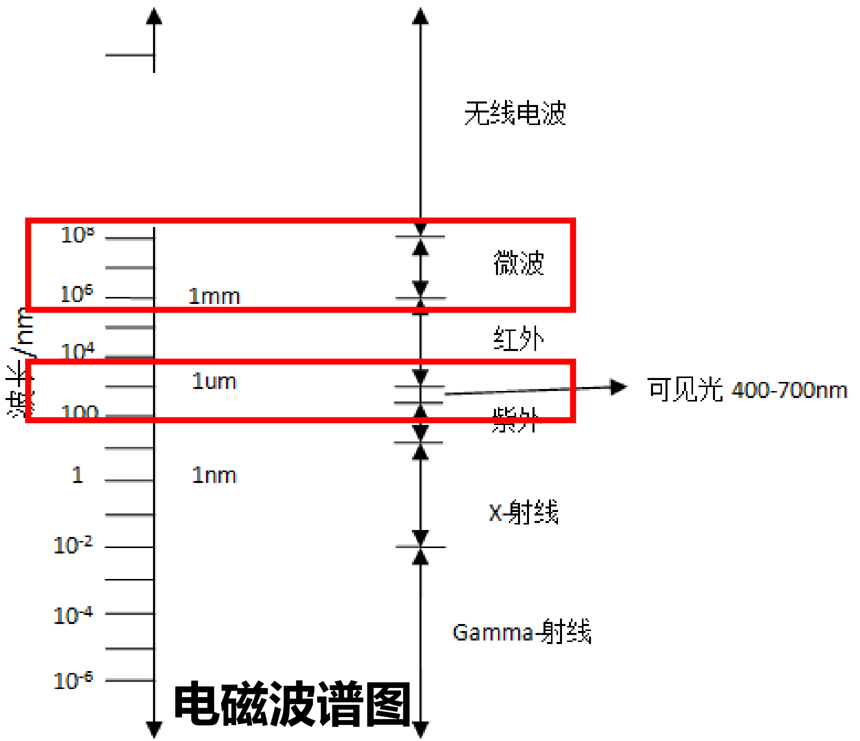
- **遥感：**通常是指使用基于卫星或飞机的传感器技术，利用传播信号（比如电磁辐射）监测和识别地球上的物体，包括对地表、大气和海洋的监测

  Remote Sensing: sensor technology based on satellites or aircraft, which uses transmitted signals (such as electromagnetic radiation) to monitor and identify objects on Earth

- **遥感分类（根据电磁波）**

  Remote Sensing Classification (based on wavelength)

  - 可见光遥感：传感器工作波段限于可见光波段之内的遥感技术（0.38-0.7μm之间）
    Visible Light Remote Sensing
  - 微波遥感（SAR）：传感器工作波段限于微波波段范围之内的遥感技术（1mm-1m之间，具有全天时全天候、不受云雨影响的特点。）
    Microwave Remote Sensing (SAR) with the characteristics of being all-weather



电磁波谱图

Electromagnetic spectrogram

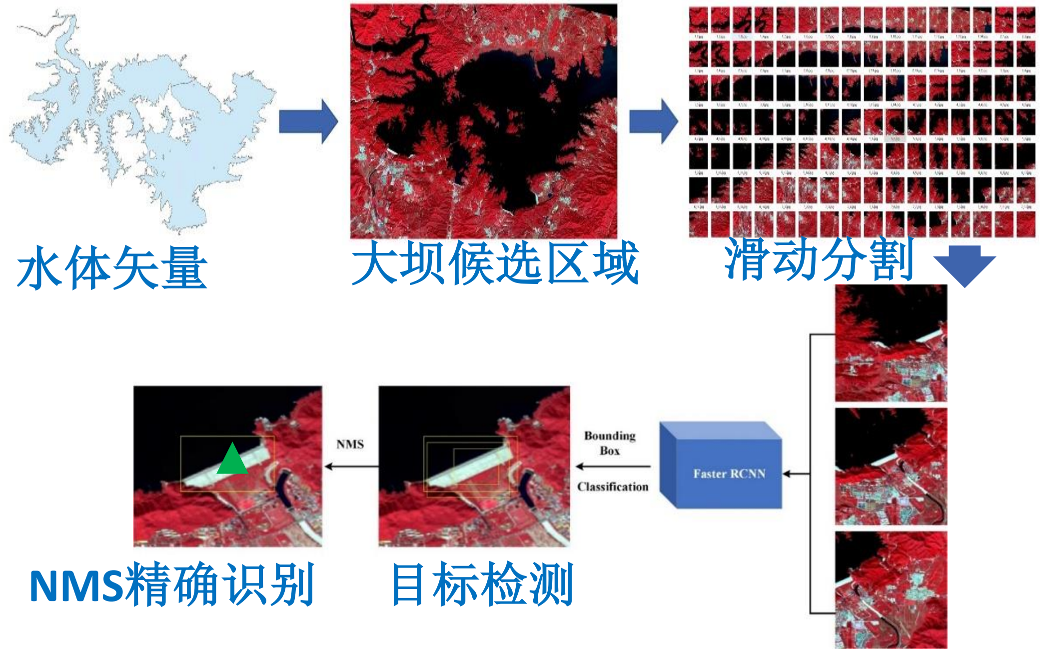
遥感监测技术及应用 Remote Sensing Monitoring Technology and Application

基于高分卫星的地物识别与特征提取 Object Recognition and Feature Extraction Based on GF Satellites

- GF影像预处理 (GF image preprocessing)
- 制作样本数据集，训练检测模型 (Dataset and model training)
- 波段运算生成特征参数影像，基于先验知识进行特征提取，获取识别候选区 (Features extracting)
- 滑动分割，目标检测 (Sliding segmentation and object detection)
- 像素坐标与地理坐标转换，生成矢量数据 (Convert coordinates to generate vector data)

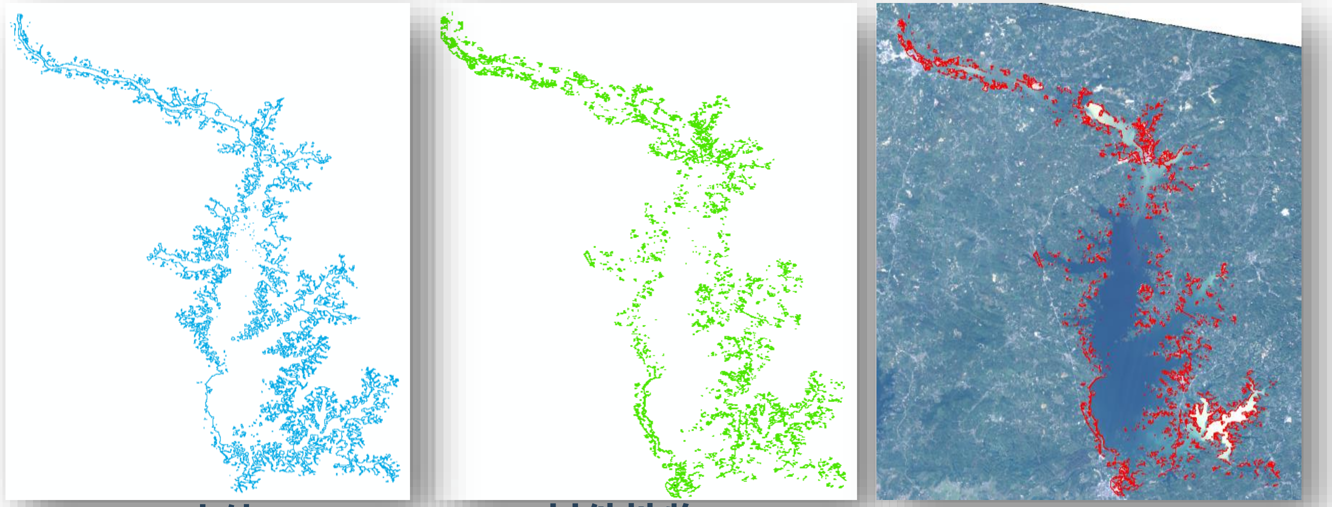
● 水库及大坝提取

reservoirs and dams identification



● 基于分类和变化监测的库区四乱目标识别

Identification of Reservoir Area illegal target Based on Classification and Change Monitoring

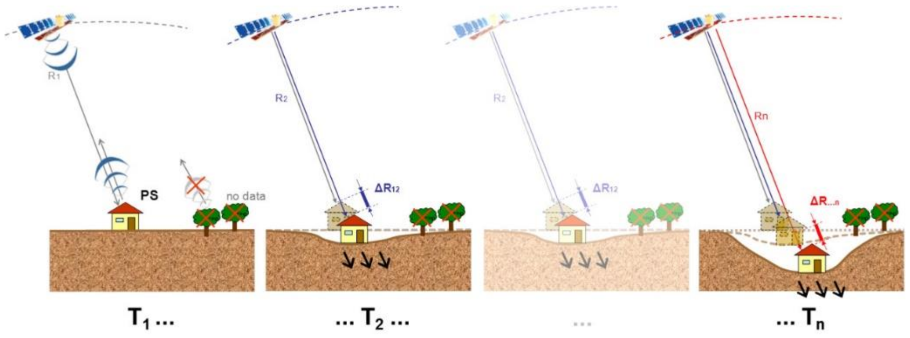


水体 Water | 其他地物 Other objectives | 疑似四乱目标 Suspected illegal target

基于SAR卫星的地表形变测量 Surface Deformation Measurement Based on SAR Satellite

- **InSAR（合成孔径雷达干涉测量）**
  - ➢ 利用对同一地区观测的两幅SAR复影像（既有幅值又有相位的影像）数据进行相干处理，通过相位信息获取地表高程信息及形变信息

    Obtaining surface elevation and deformation information through phase information of SAR



- **库岸滑坡体形变监测**

  Monitoring of Landslide Deformation on Reservoir Bank
  - ➢ 三峡库区滑坡稳定性监测（Sentinel-1,2016-03至2020-03共111景）—朱同同，2021

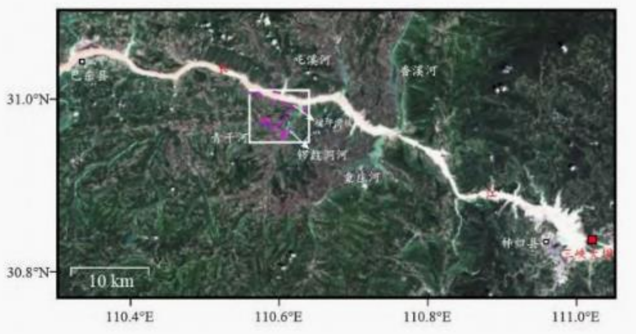


图1 实验区

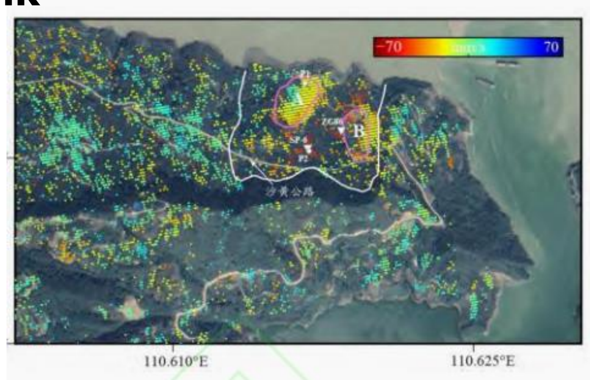


图4 树坪滑坡平均变形速率图

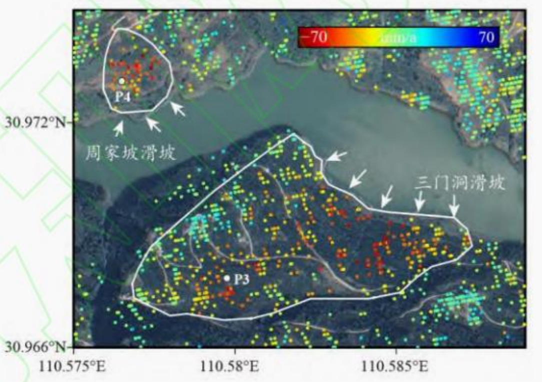


图7 三门洞和周家坡滑坡平均变形速率图

Stability Monitoring of Landslides in the Three Gorges Reservoir Area

卫星遥感水利工程应用 Satellite Remote Sensing Applications in Hydraulic Engineering

意大利瓦依昂大坝库区滑坡灾害

Landslide disaster in the Vajont dam Reservoir of Italy

- 1959年秋竣工，1960.2蓄水，1963.10.9水库南坡一块南北宽超过500米、东西长约2000米、平均厚度约250米的巨大山体滑坡发生

  On 1963.10.9, a massive landslide occurred on the southern slope of the reservoir. The landslide covered an area exceeding 500 meters in width from north to south, approximately 2,000 meters in length from east to west, with an average thickness of about 250 meters.

InSAR监测能否提前预警?

Can InSAR monitoring provide an early warning?

应用问题分析 Challenges in Application

- 卫星遥感在水利工程中已有部分应用，但相对较少，研究还不够深入，与工程已有监测数据缺少互证融合，精度和时效性还难以满足工程实际需求

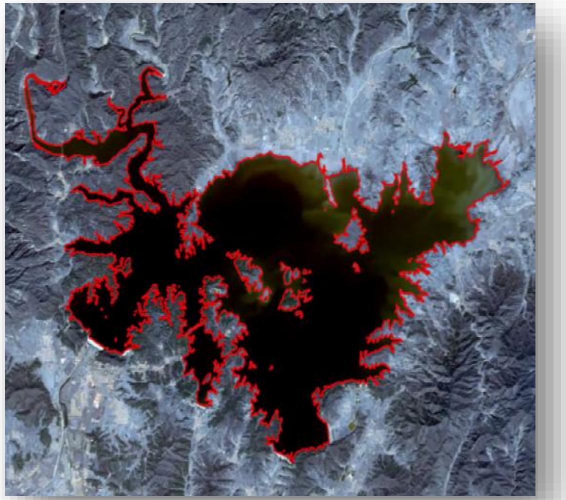
  The accuracy and timeliness are still challenging to meet the practical needs of the engineering

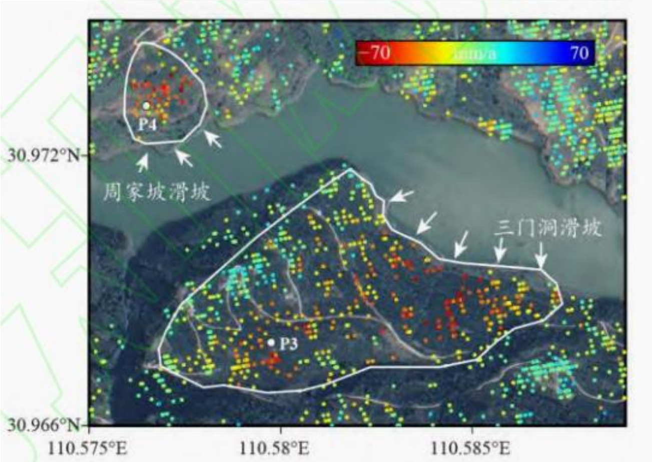
  - 光学遥感：受天气影响大且精度有限

    Optical remote sensing: Susceptible to weather conditions and limited in accuracy

  - SAR&InSAR：成像不受光线、气候和云雾限制，干涉测量精度理论可达cm级，实际应用受地形起伏、植被覆盖、大气等去相干因素影响，不够稳定

    SAR & InSAR: Practical application stability are affected by factors such as terrain variations, vegetation cover, atmospheric conditions





多源遥感数据融合和多种雷达干涉技术结合增强时空分辨率和地物识别能力，并与无人机空中摄影测量、工程地面先验监测信息等进行互证融合 Mutual verification and fusion of multi-source remote sensing data

Part 2

工程区大范围形变遥感精准监测

Precise Remote Sensing Monitoring of Large-Scale Deformations in Engineering Areas

河口村水库表面形变遥感监测 RS Monitoring of Surface Deformation in Hekou Reservoir

河口村水库为选用研究工程

- 地理位置：济源市，黄河一级支流沁河上
- 工程等级：大（2）型水库，总库容3.17亿m^3
- 大坝：面板堆石坝，最大坝高122.5m

Hekou Village Reservoir is located in Jiyuan City, Yellow River tributary, with a concrete face rockfill dam that reaches a maximum height of 122.5 meters.

研究内容（Research Content）：

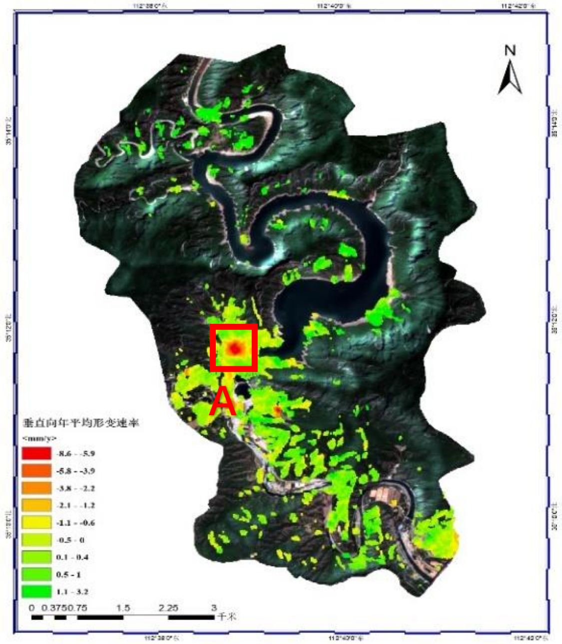
- 通过时序InSAR方法对河口村水库大坝形变进行遥感监测实验分析

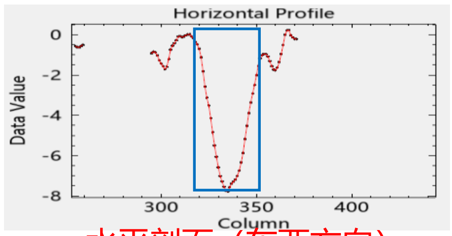
Experimental analysis of remote sensing monitoring of dam deformation in Hekou Reservoir using time-series InSAR method.

工程区大范围形变遥感监测 RS Monitoring of Large-Scale Deformation in the Engineering Area

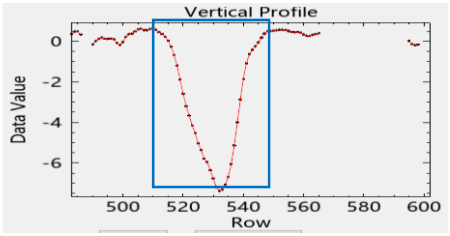
采用 PS/SBAS-InSAR 方法对 2017.10-2022.12期间的河口村水库工程区进行了大范围形变监测（151景Sentinel1A升轨数据），发现大坝所在区域存在明显的沉降变形（10mm/y）

Extensive deformation monitoring in the engineering area of Hekou Reservoir was conducted, using the PS/SBAS-InSAR method with data from 151 Sentinel-1A ascending orbits between October 2017 and December 2022. Significant subsidence deformation in the dam area was identified, with a rate of 10 mm per year.

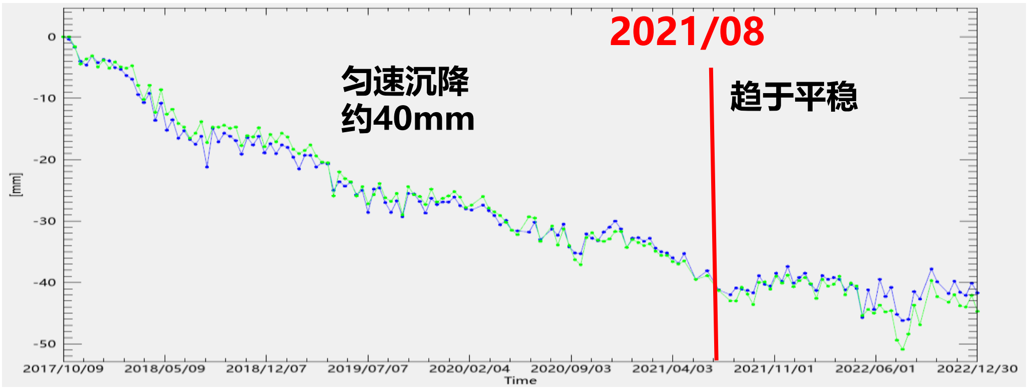




水平剖面（东西方向）



垂直剖面（南北方向）

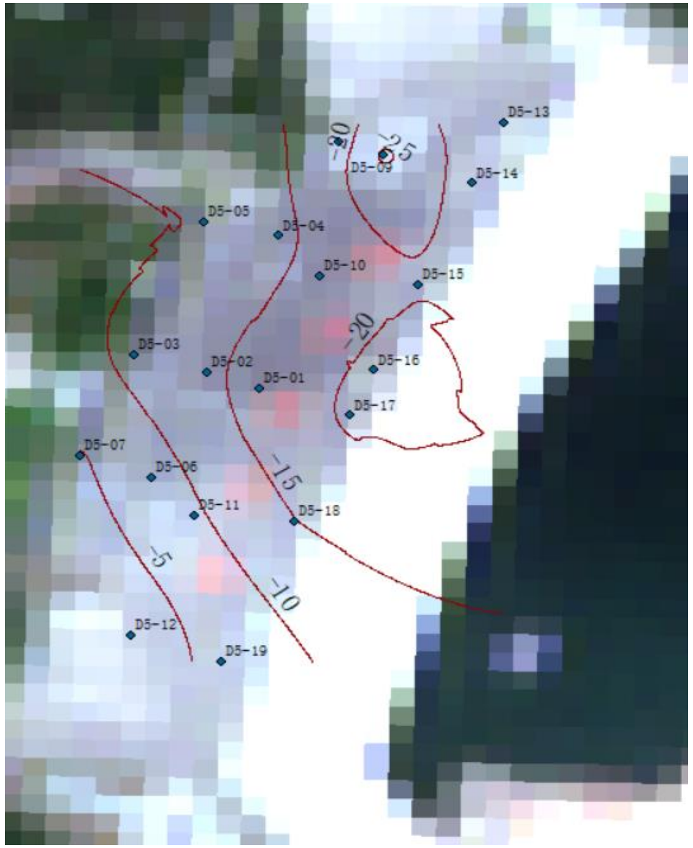


A沉降区及部分点形变序列
Subsidence Area and Deformation Time Series at Selected Points

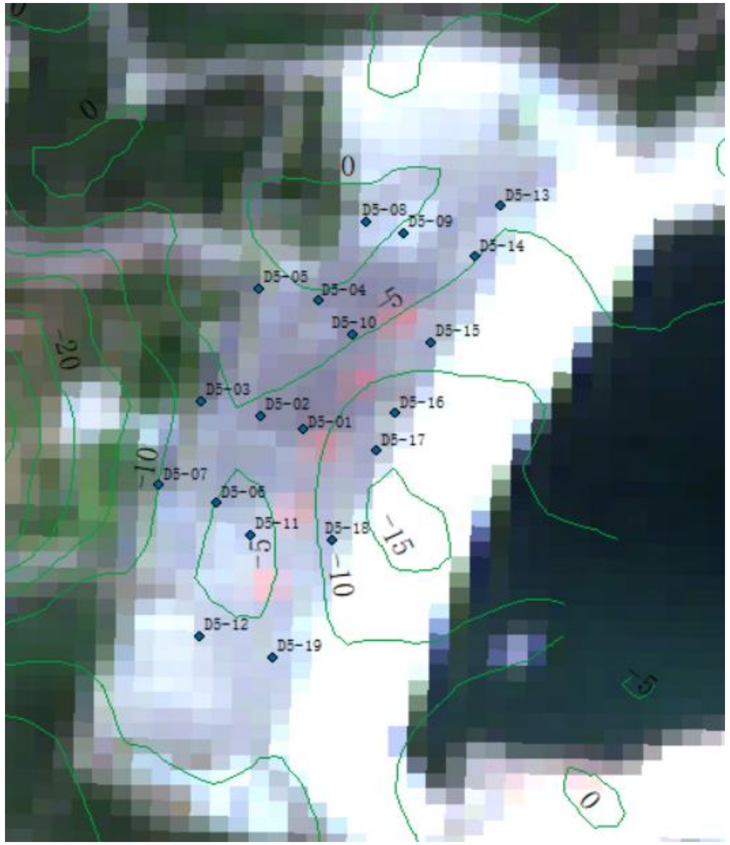
大坝表面变形遥感精准监测 Precise Remote Sensing Monitoring of Dam Surface Deformation

对比河口村大坝2017.10-2022.12实测数据、SBAS、PS累积形变量结果，SBAS-InSAR更适合水库大坝林木遮挡的复杂地形条件，精度更高，与实测值最大误差在6mm以内

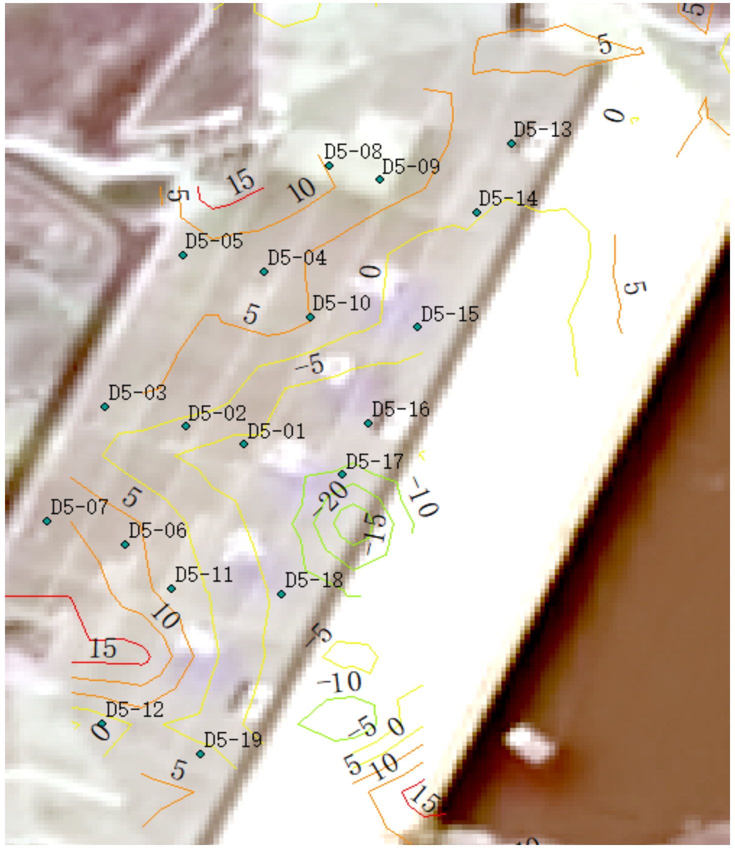
SBAS-InSAR provides higher accuracy, with a maximum error of within 6 mm compared to the ground truth measurements



实测累积形变量等值线
Contour Lines of Measured Cumulative Deformation



SBAS累积形变量等值线
Contour Lines of SBAS Cumulative Deformation

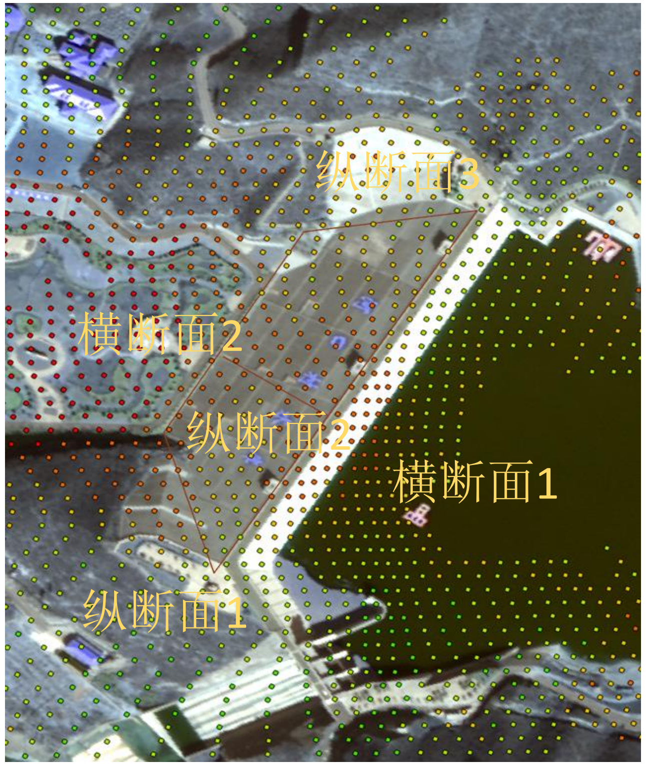


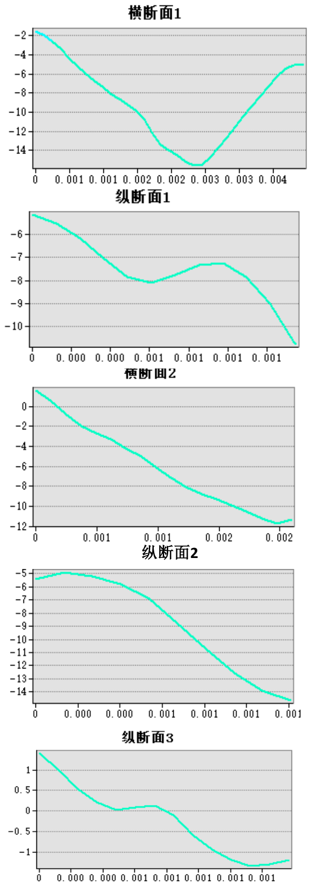
PS累积形变量等值线
Contour Lines of PS Cumulative Deformation

大坝表面变形遥感精准监测 Precise Remote Sensing Monitoring of Dam Surface Deformation

大坝SBAS-InSAR监测结果的剖面变形规律符合工程实际
Analysis of profile patterns in the dam's SBAS-InSAR monitoring results

■ 大坝沉降横纵断面分析
Horizontal and Vertical Cross-Sections of Dam Subsidence





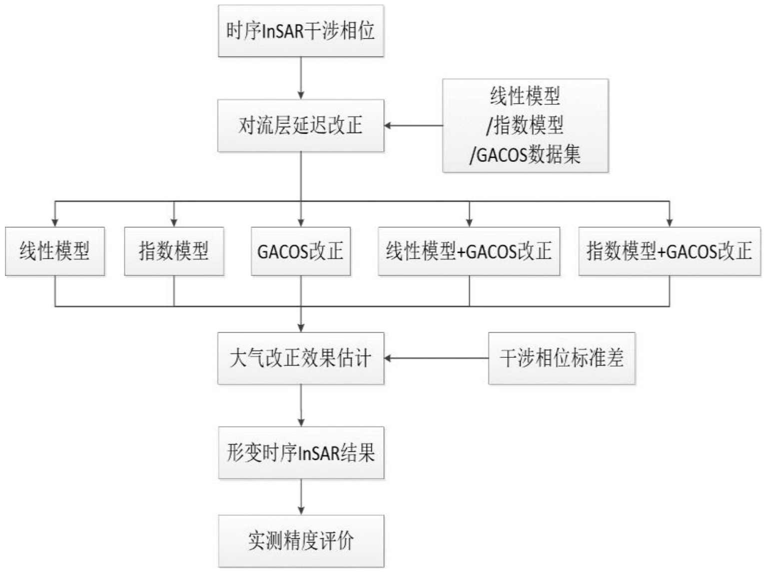
大坝总体上表现为沉降趋势，中间纵断面相较于两侧沉降量较大，横断面也可以看出大坝中间累积形变量大于两侧坝肩。大坝整体呈现河床部位比两坝肩形变大、坝顶比坝身形变大的特征，符合堆石坝的沉陷变形规律

The dam exhibits an overall subsidence trend, with the central longitudinal section experiencing greater subsidence compared to the two lateral sections. This is also evident from the cross-sections, where the cumulative deformation in the middle of the dam is greater than at the dam shoulders, which show relatively stable behavior. The dam as a whole exhibits a pattern of greater deformation in the center than at the shoulders and greater deformation at the top than at the waist, consistent with the subsidence deformation characteristics typical of rock-filled dams.

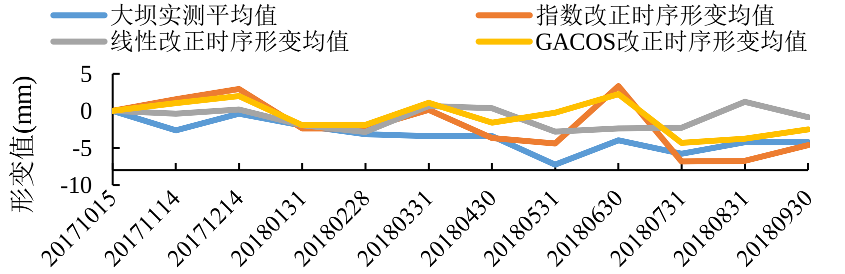
大坝表面变形遥感精准监测 Precise Remote Sensing Monitoring of Dam Surface Deformation

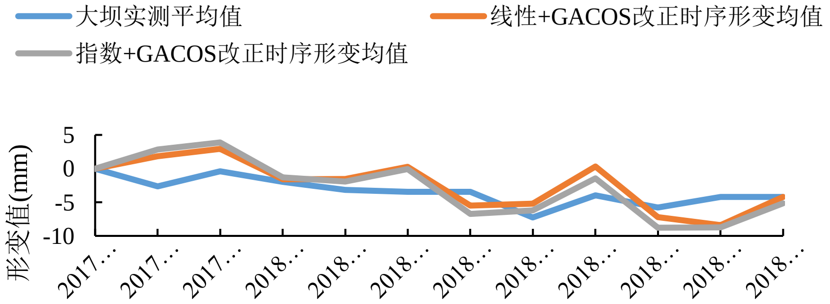
针对库坝区地势复杂特点，提出结合线性模型、指数模型和GACOS数据集的**时序InSAR大气二次改正**方法，削弱了大气延迟和复杂地表对干涉精度的影响，监测误差进一步减小到5mm以内

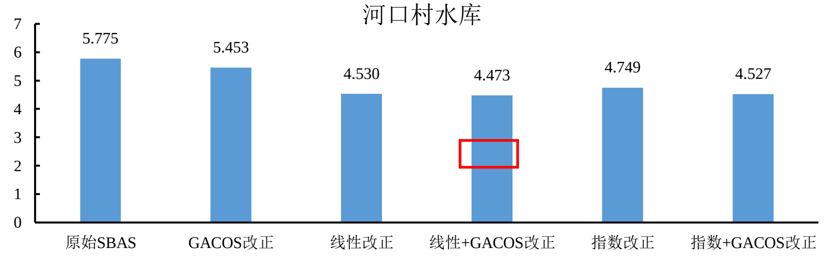
Secondary Atmospheric Correction for Time-Series InSAR further reduces the monitoring error to within 5 mm



时序InSAR对流层延迟改正方法流程
Workflow for Tropospheric Delay Correction in Time-Series InSAR







平均形变中误差对比(mm)
Comparison of Mean Deformation Errors (mm)

大气改正方法适用于水库一定地势起伏区域，可改进提高监测精度

This method is suitable for regions with certain terrain variations, and can be improved to enhance monitoring accuracy.

Part 3

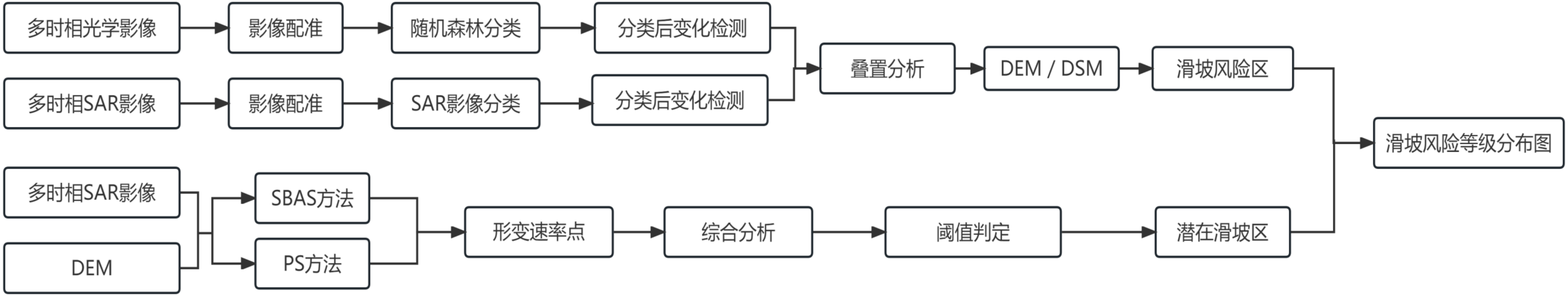
水库大坝运行风险遥感识别

Remote Sensing Identification of Reservoir Dams Operation Risks

潜在滑坡风险区遥感识别 Remote Sensing Identification of Potential Landslide Risk Areas

多源卫星遥感影像融合分析的库岸滑坡体识别方法：基于多时相光学影像地物分类识别地物明显变化区，融合地形坡度坡向等划定潜在滑坡风险区； 对时序InSAR形变时序监测结果进行局部热点分析和核密度分析，精准识别潜在滑坡风险范围

Identification of potential landslide risk areas based on multi-temporal optical images for the recognition of significant land-cover changes, and combining local hotspot analysis and kernel density analysis of time-series InSAR deformation results to accurately delineate potential landslide risk zones.

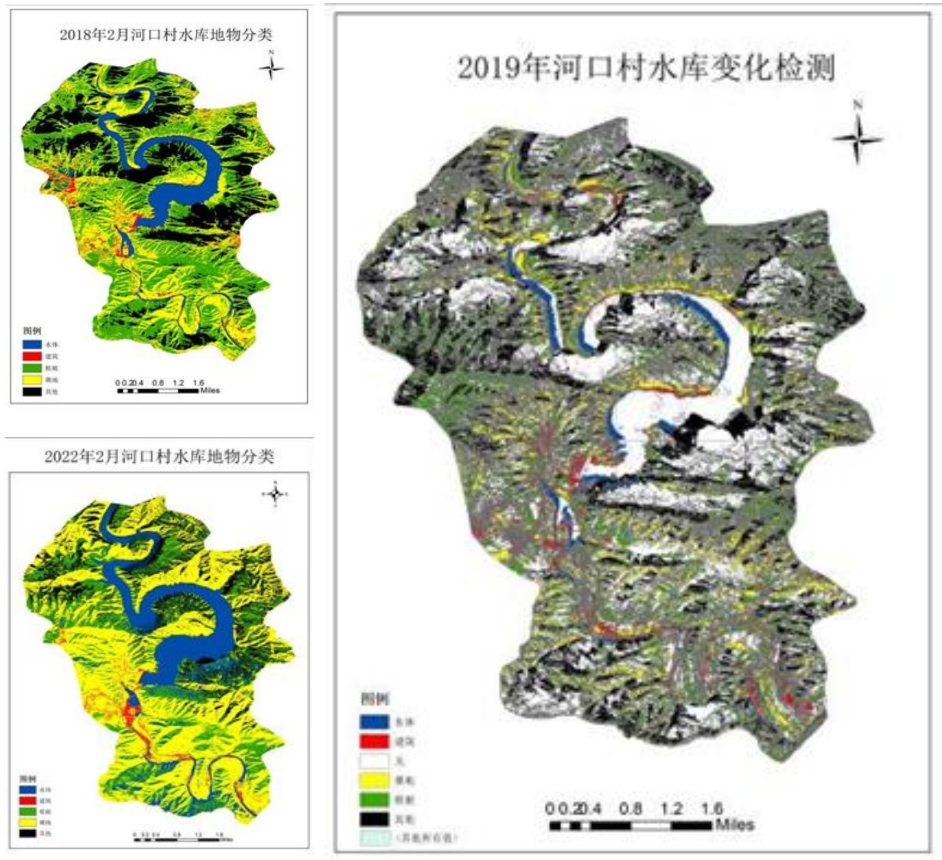


光学遥感与InSAR监测融合的滑坡精准识别技术路线
The Technical Roadmap for Precise Landslide Identification by Integrating Optical Remote Sensing and InSAR Monitoring

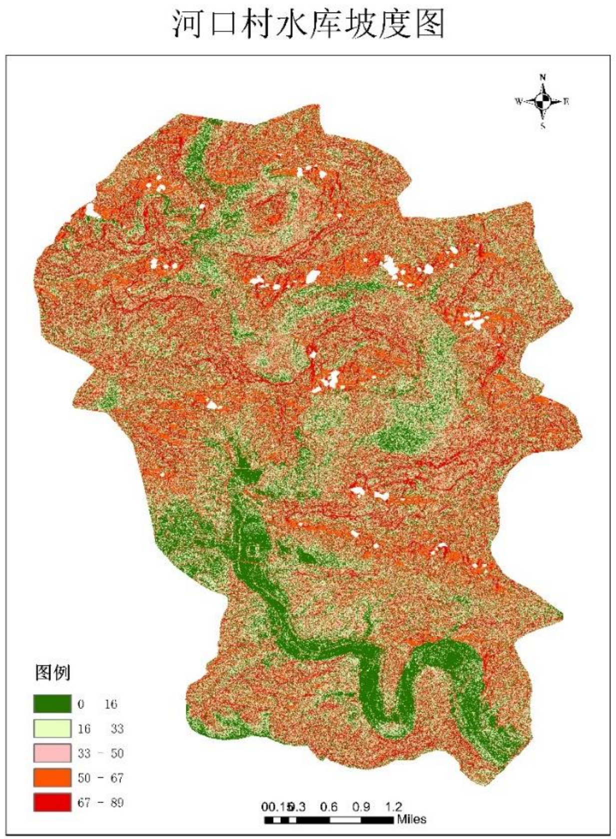
潜在滑坡风险区遥感识别 Remote Sensing Identification of Potential Landslide Risk Areas

利用随机森林方法对光学和雷达影像进行地物分类，变化检测提取影像分类后的变化结果，标识地物覆盖类型发生变化的区域，并结合DSM及坡度、坡向数据，初步划定潜在滑坡体风险区域

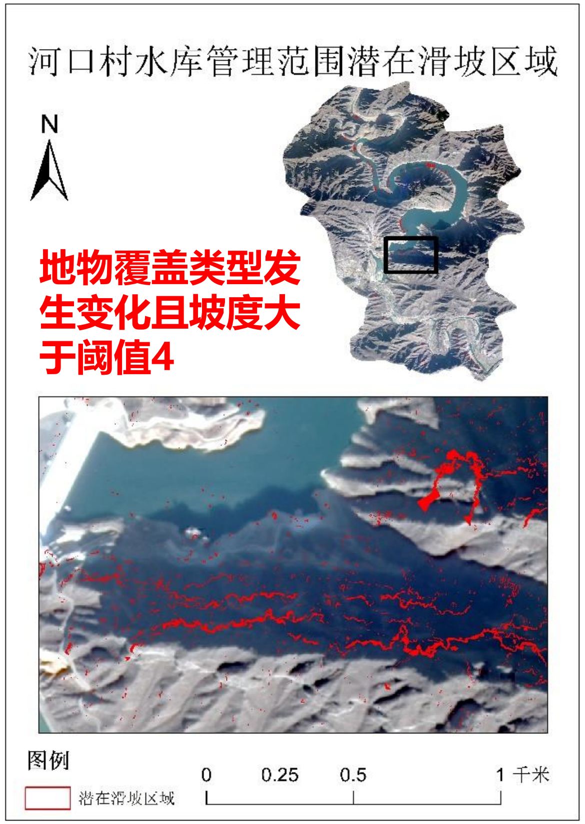
Utilizing the RF method for land-cover classification to extract change results and identify areas with changes. Combining DSM data with slope and aspect information to preliminarily delineate potential landslide risk zones



地物覆盖类型变化检测
Detection of Land Cover Type Changes



DSM重分类后的坡度（5级）
Slope Reclassified from DSM

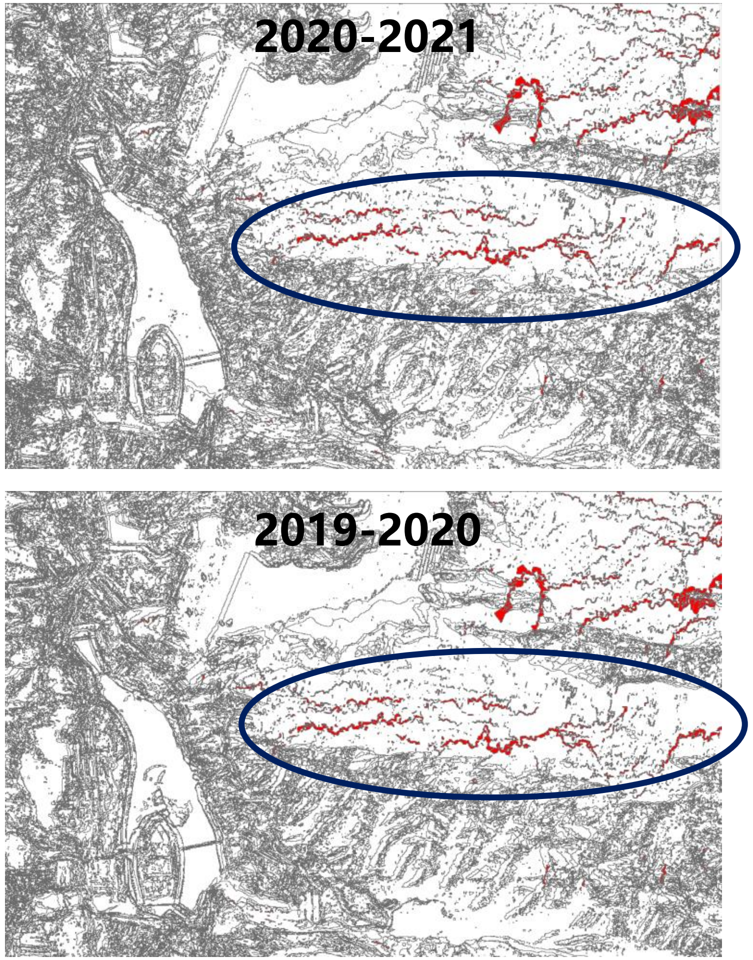


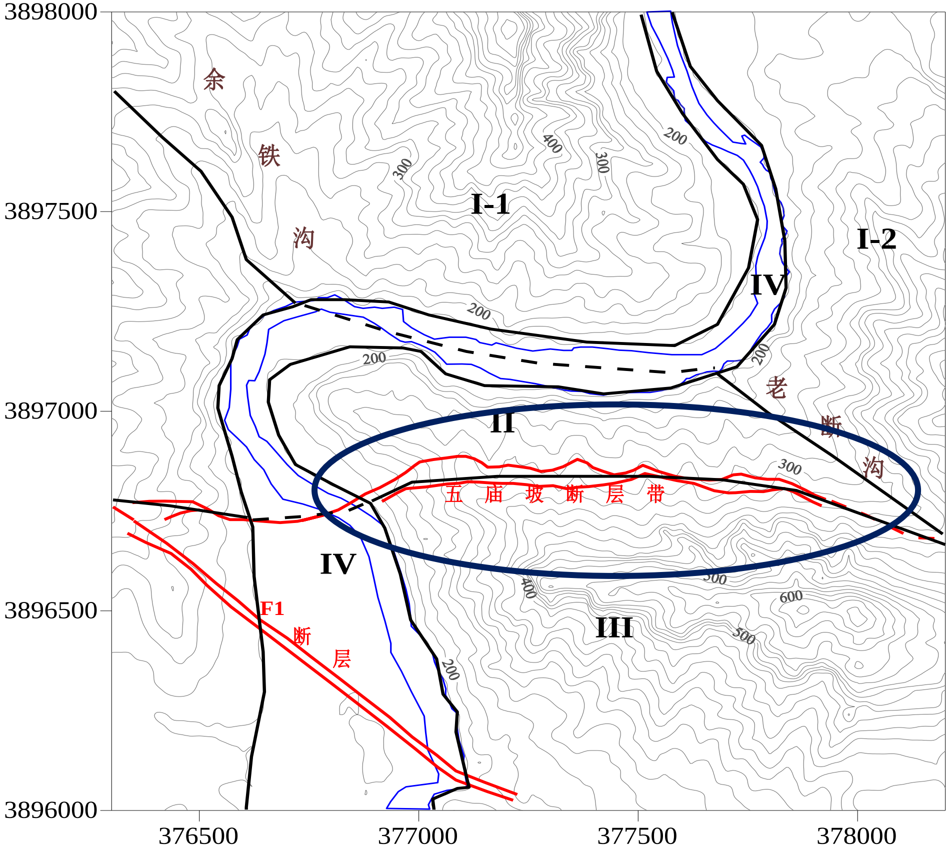
潜在滑坡体风险区识别结果
Identification Results

潜在滑坡风险区遥感识别 Remote Sensing Identification of Potential Landslide Risk Areas

识别的潜在滑坡体风险区与水库坝区地质构造图反映的主要断层带位置分布总体一致

The identified potential landslide risk zones align overall with the distribution of major fault zones indicated by the geological structure map of the reservoir dam area





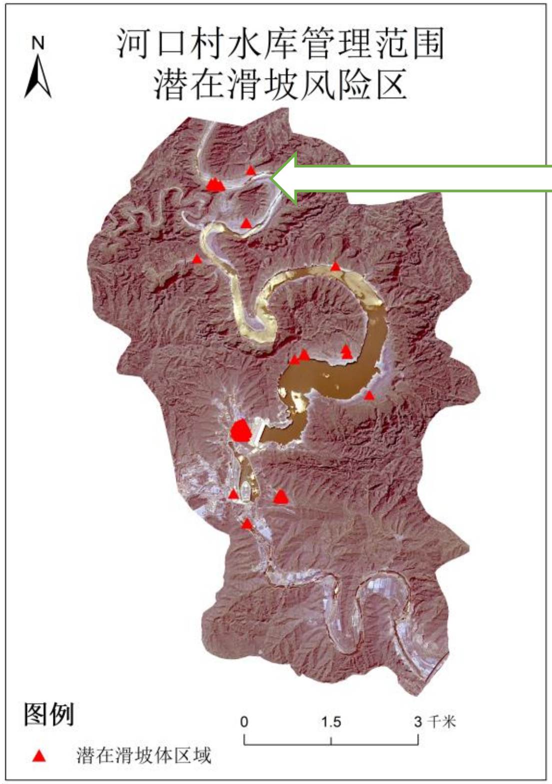
I-1—单斜构造双层含（透）水层区（右岸） I-2—单斜构造双层含（透）水层区（左岸）

II—龟头山褶皱断裂混合透水层区 III—断层密集带低水位区 IV—河床含水层区

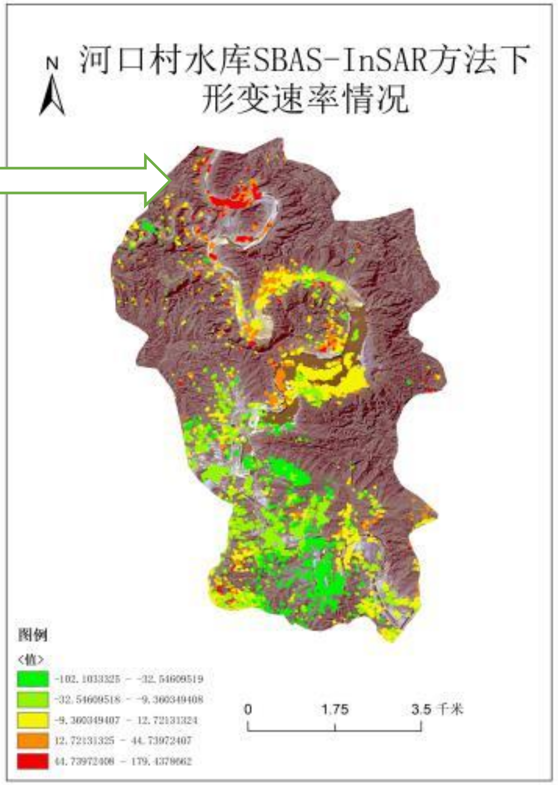
潜在滑坡风险区遥感识别 Remote Sensing Identification of Potential Landslide Risk Areas

基于SBAS-InSAR形变监测开展了库区潜在滑坡隐患识别和分析，将2020-2022年形变速率大于5mm/year的区域视为滑坡体风险区，对比发现多源遥感影像获得的风险区具有一定重合性

Based on SBAS-InSAR monitoring， identification and analysis of potential landslide hazards were conducted in the reservoir area (Sentinel-1A、PALSAR HH). Regions with deformation rates exceeding 5 mm/year between 2020 and 2022 were considered landslide risk zones. A comparative analysis revealed a certain degree of overlap between the risk zones obtained from multiple remote sensing images.



SBAS-InSAR（Sentinel）



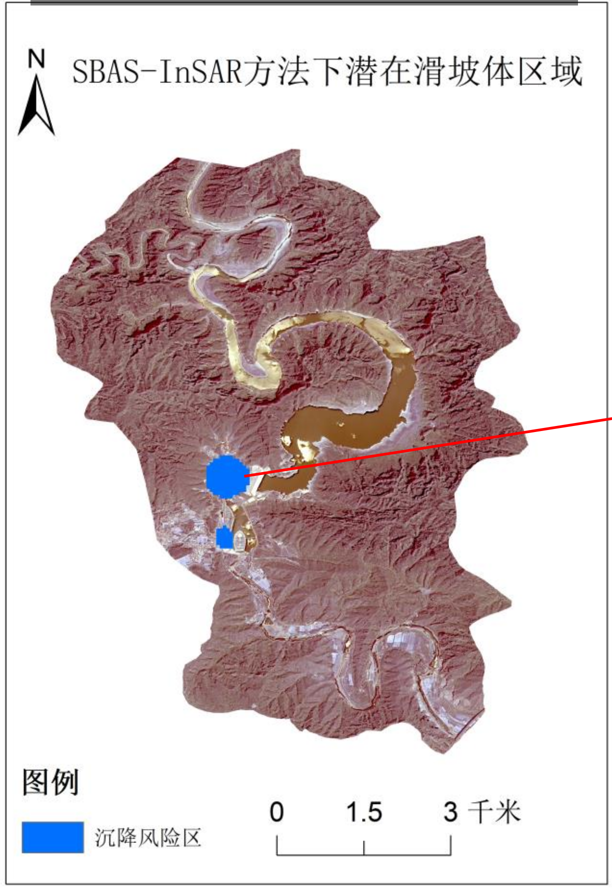
SBAS-InSAR（PALSAR）

潜在滑坡风险区遥感识别 Remote Sensing Identification of Potential Landslide Risk Areas

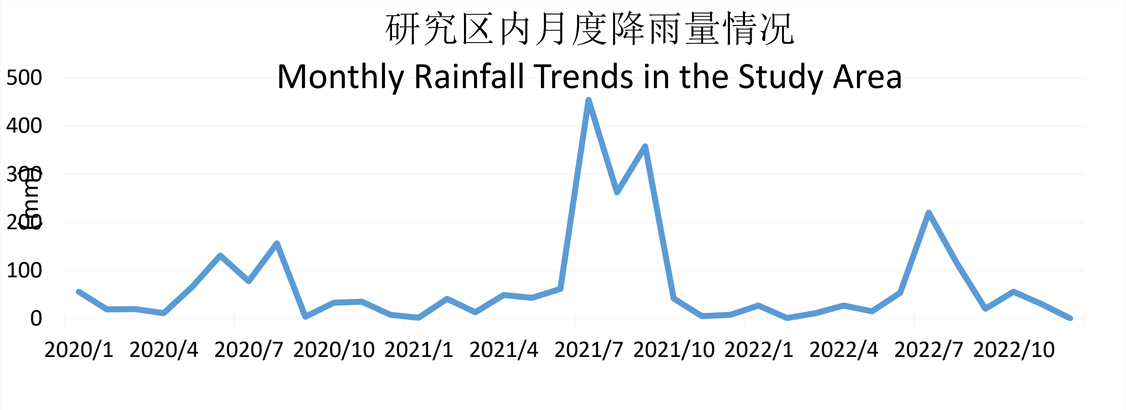
设置阈值来衡量地表形变稳定性，利用局部热点分析和核密度分析法获取精准滑坡范围及形变趋势

A threshold was established to assess the stability of surface deformation points, areas with rates exceeding 2 mm/year were considered as unstable regions. Then local hotspot analysis and kernel density analysis methods were employed to precisely determine the landslide extent and deformation trends.

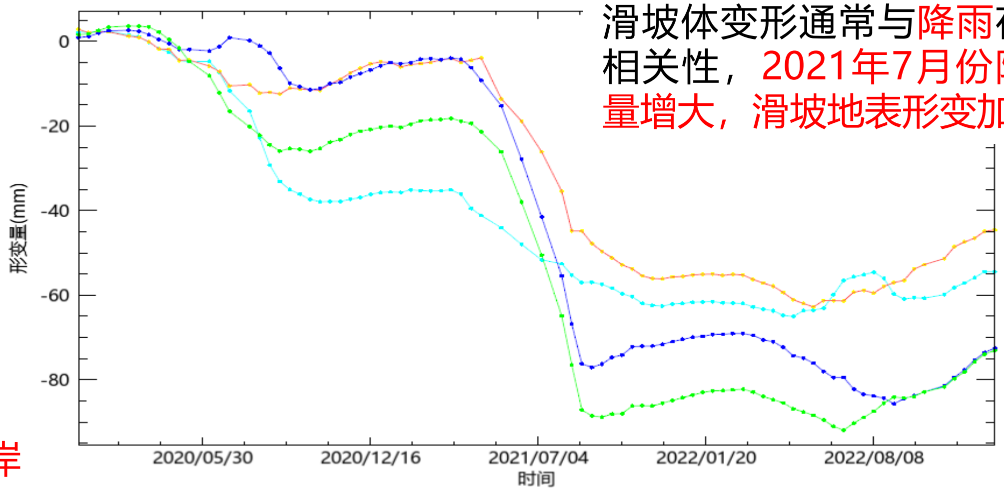
SBAS-InSAR方法下滑坡体分布情况
Landslide Distribution Using the SBAS-InSAR Method



沉降风险区位于大坝西侧、下游河滩左岸
The subsidence risk zones were located on the western side of the dam and the left bank of the downstream riverbed.



济源市降雨量变化情况
Changes in Precipitation in Jiyuan City



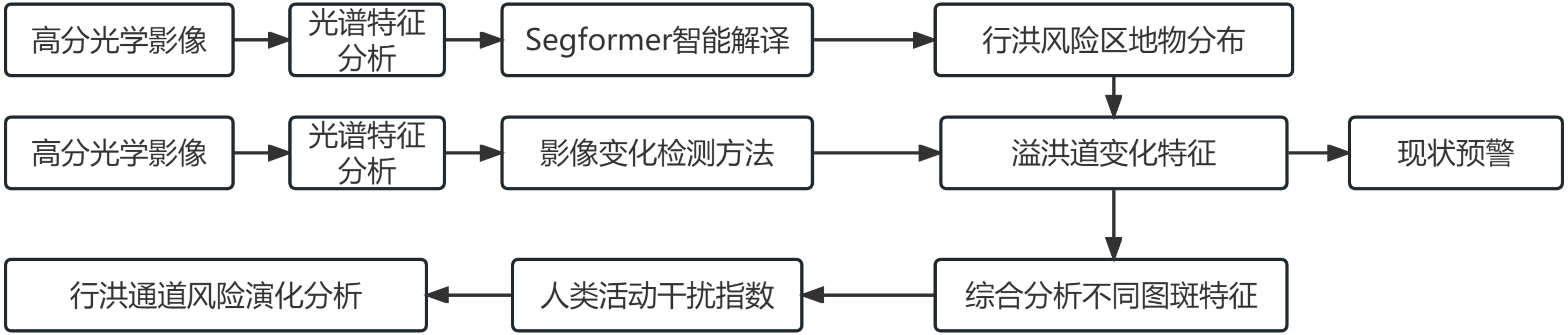
滑坡体变形通常与降雨存在相关性，2021年7月份降雨量增大，滑坡地表形变加速

潜在滑坡地区地表时序形变情况
Temporal Surface Deformation in Potential Landslide Areas

人类活动与水毁风险识别 Identification of Human Activities and Water-Related Disaster Risks

多时相光学智能解译与变化检测的人类活动与水毁风险精准识别： 基于SegFormer的行洪风险区临河房屋与建设用地等的智能解译，获取行洪风险区地物分布；开展多时相影像变化特征的行洪通道侵占与水毁情况识别，可进行行洪水风险演化分析

Utilizing SegFormer for Intelligent Interpretation to Obtain Land Cover Distribution in Flood Risk Areas. Conducting Identification of Encroachments on Flood Channels and Water Damage to Analyze Flood Channel Risk Evolution



技术路线图
Technology Roadmap

人类活动与水毁风险识别 Identification of Human Activities and Water-Related Disaster Risks

遥感影像变化检测精细提取某水库洪涝灾害损毁数据

Change detection in remote sensing images can accurately extract data on reservoir flood disaster damage

正在开展工作 Work in Progress

区分水库大坝环境风险、工程风险和人类活动风险遥感变化特征进行识别，基于遥感增量信息推演工程风险态势，实现风险源快速识别与预警

Identifying based on remote sensing change characteristics of different risks, deducing the engineering risk situation, and achieving rapid identification and early warning

不同风险类型 Risk Classification

危岩体滑移 | 滑坡体崩塌 | 岸坡冲刷

环境风险 Environmental Risk

建筑物变形 | 严重渗流 | 泄洪水力影响

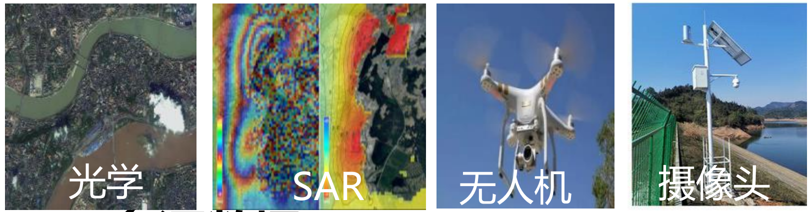
工程风险 Engineering Risk

库区侵占 | 行洪通道侵占

洪水风险区土地利用

人类活动风险 Human Activity Risk

风险目标识别



多源数据 Multi-Source Data

风险目标	辨识方法
潜在滑坡体	误差消除算法 多源监测融合
结构变形	无人机影像自动匹配算法、三维建模
工程渗流	渗流特征识别 温差指标法
泄洪水力冲刷	智能图像识别方法
人类活动风险	影像增强与融合 非/监督分类 机器学习方法

辨识方法 Identification Methods

增量风险预警

防洪风险预警

防洪推演评估

环境工程风险预警

大小/范围、变化速率准则

风险演变特征分析

位置、大小/范围、变化速率跟踪监测分析

风险源遥感识别

（神经网络、机器学习）

正在开展工作 Work in Progress

基于水库大坝特点分类研究工程遥感监测要素和监测应用技术，包括卫星组网及优化配置模式，多源遥感高效整编、地面监测互证模式等，形成**水库大坝运行风险遥感监测技术方法体系**及多源监测优化配置应用模式

Based on the classification of reservoir dam characteristics, research on engineering remote sensing monitoring elements and monitoring application technologies, and form a method system for remote sensing monitoring of reservoir dam operation risks

01 **卫星组网及优化配置模式**
Satellite networking and optimized configuration mode

02 **星源业务化整编及信息融合**
Satellite source business integration and information fusion

03 **工程应用技术方案**
Engineering Application Technology Plan

04 **地面监测互证模式**
Ground monitoring mutual certification mode

水库大坝遥感监测预警技术方法体系

Remote Sensing Monitoring and Early Warning Technology Methodology for Reservoir Dams

Part 4

小结与展望

Summary and Outlook

小结与展望 Summary and Outlook

- 遥感监测对弥补水库大坝地面监测不足，变革工程安全监测模式具有重要意义

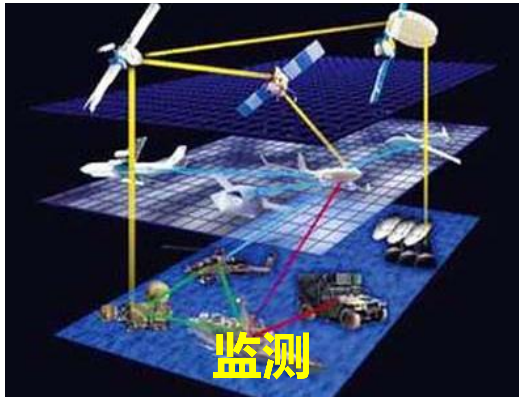
Remote sensing monitoring can compensates for the lack of dam ground monitoring and transforms the engineering safety monitoring mode

- 在水库大坝安全管理中的业务化应用还不够深入，存在遥感监测精度和时效性问题

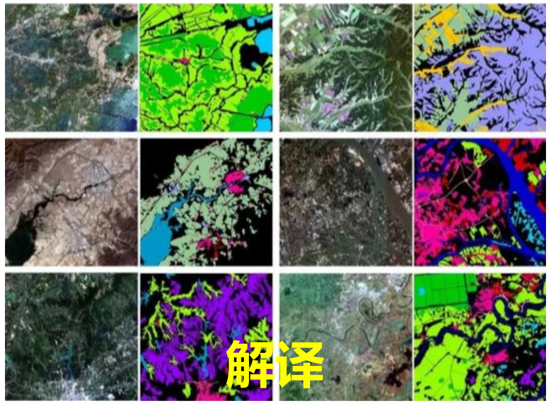
The business application in the dam safety management is not deep enough, and there are problems with the accuracy and timeliness of remote sensing monitoring

- 探索研究水利工程遥感监测预警技术，提升遥感监测工程应用能力，是新阶段水利高质量发展建设数字孪生水利工程、现代化水库运管矩阵的核心支撑技术，需求和前景广阔

Exploring remote sensing monitoring and early warning application technology is the core support for high-quality development and construction of modern reservoir operation management matrix in the new stage, with broad demand and prospects



Monitoring



Interpretation

Model

Application

Thank you for your attention!

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