1. Libration Point Navigation Concepts Supporting the Vision for Space Exploration

* 1. <https://www.researchgate.net/profile/C_Gramling/publication/4707030_Libration_Point_Navigation_Concepts_Supporting_Exploration_Vision/links/5436c54f0cf2643ab988891b.pdf>
  2. ***Examines navigation accuracy achievable for lunar exploration, using a nav sat at a libration point, augmented by gps***
  3. ***Compare libration to lunar orbit for nav relay architectures***
  4. ***GPS Issues for Cis-lunar trajectories***
  5. Comparison of 3 lunar navigation constellations(see table for delta v costs & space loss)
     1. Elliptical lunar orbits (6 sats)
     2. Circular lunar orbits (6 sats)
     3. Large lissajous at EML2 (4 sats)
  6. GPS availability durin TLI
     1. Baseline case
        1. Acquisition/tracking of 25 dBHz(-184 dBWatts min ambient power), 10 dB antenna, also considered cases of 18 dbHz and 11dBHz
        2. Geometric ubstruction from earth assumes constant 6378.14 km and 50 km atmosphere mask
        3. Single frequency L1 C/A code, transmitter power assumed to be block II/IIA GPS sats
     2. Typically, 2 or more sats in view out to 18 earth radii, after which rarely more than 2, never more than 3
     3. Near l1 only 1 sat is typical for baseline case, with significant improvement when using 11dBHz receiver
  7. Navigation analysis
     1. Done using GEONS(an EKF), measurement model includes GPS with other sensors/comms, sate vector includes position/velocity (absolute or relative), drag/radiation pressure corrections
     2. With 1-way Doppler and gps pseudorange,accuracies within 1 km and 5cm/sec were feasible

1. En route to the Moon using GNSS signals

* 1. <https://www.researchgate.net/profile/Giovanni_Palmerini/publication/229351299_En_route_to_the_Moon_using_GNSS_signals/links/550fe4f80cf21287416c610b.pdf>
  2. ***Evaluates carrier-to-noise levels during different phases compared to current receivers***
  3. ***Possible software receiver application***
  4. Sufficient Signal to noise from main, second and third lobes for acquisition out to geo
  5. European Student Moon Orbiter taken as sample mission, require 9 month spiral trajectory to moon, allowing mapping of gps signals wrt to radius and sight angle
  6. Mission design
     1. GPS config from week 388(feb 07) with sat prn 1 through 31 (except 15) considere available
     2. See table for space craft initial parameters
     3. Initial time is march 3 2011, 0:00:00 UTC with space craft firing tangentially during whole 9 month mission
     4. 3 phases(gto-like, outside gps constellation, moon altitude)
     5. Accuracy achievable in high orbtis depends on GDOP
  7. Nav system model
     1. Four antenna (facing out of plane and along z and r axis)
     2. SNR=Pr-10logTsys(190k)+228.6 +LNf(-3dB)+Li(-1.5dB)
        1. SNR of 35dBHz for signal acquisition threshold
     3. Lowering signal to noise threshold increases time interval in which signals can be acquired and kinetmatic state determined suggested that 20 dB Hz should be minimum
  8. Software GNSS receiver
     1. 2 options
        1. Use ground based computers for data processing
        2. On board processing (FPGA style)
  9. Remarks
     1. Could reduce costs, due to increased autonomy

1. Use of Weak GNSS Signals in a Mission to the Moon

* 1. <http://spcomnav.uab.es/docs/conferences/Moon_GNSS2014.pdf>
  2. ***ESA Moon-GNSS project seeks to determine feasibility of weak signal tech to improve navigation accuracy, reduce cost, and improve autonomy***
  3. ***Challenges faced***
     1. ***Less visibility,***
     2. ***low signal strength,***
     3. ***poor sat geometry,***
     4. ***earth/moon signal occultation,***
     5. ***space craft dynamics***
  4. ***Identification of receiver requirements***
     1. ***Impact of requirements on receiver module architechture and algorithms(Weak signal processing, filtering, and navigation)***
  5. ***Integration of gnss with other sensors(IMU/accelerometers)***
  6. ***Demonstration tests carried out to cover all mission phases***
  7. Scenario description(ESA lunar lander mission)
     1. 8 phases
        1. LTO
        2. 2through 4 are phase orbits around moon to reach LLO
        3. LLO
        4. Coasting to surface
        5. Descent and landing
        6. Surface ops
     2. Analysis done of GNSS signals arriving near moon to derive receiver requirements
     3. GPS/Galileo considered
     4. Moon GNSS considered
     5. Tracking down to 15dBHz feasible but considers range between 10 and 15
     6. Most signals from secondary lobe
     7. Receiver requirments
        1. Low noise front end
        2. High stability local oscillator
        3. Memory required to record and store several hundred milli seconds
     8. Overview of space receivers
        1. MosaicGNSS
        2. Navigator
        3. Phoenix in PROBA3
        4. Software receiver for MAGIA mission
        5. All listed reach as low as 20-25dBHz
     9. Architecture of receiver module
        1. Snap shot architecture
           1. Robust against sever signal attenuation and uncertain dynamics
           2. Allows for long coherent/non-coherent integration intervals
           3. Navigator is following this development
        2. Propose the architecture used in DINGPOS project
           1. Developed for indoors
           2. Compatible with GPS/Galileo
           3. Use assistance info to limit time-freq search range

Doesn’t need to integrate INS at signal level

* + - 1. See block diagram
      2. Search for correlation values cin time frequency grid can be done using only FFT operations
      3. ESA patented Double-FFT method for low C/N0 values
    1. Moon-GNSS nav filter trade-off
       1. Table of sensors for 4 main phases
       2. Hybridization trade-off between performance and complexity
          1. Loose coupled, tight coupled, deeply integrated
       3. Tight coupled is preferred
          1. Allows classical nav filter techniques
          2. Use every single GNSS measurement
       4. Use of EKF
          1. Modified to include gnss measuments in dedicated second update block to save computational resources
  1. Proof of concept
     1. Developed in matlab/Simulink
     2. Scenario generator module
        1. Simulates GNSS signal values
           1. Range distance
           2. Doppler expected
           3. C/N0 values
     3. GNSS receiver module
        1. Generate fractional pseudo/frequency observables
        2. Uses SGM results as input
        3. 2 main parts
           1. Data handling and config
           2. Equivalent C/N0 computation and generation of simulated observables
     4. Navigation filter module
        1. Takes in GRM results and sensors results
        2. Outputs estimated position and velocity
  2. Test cases
     1. Select frequency band
     2. Select optimum moon gnss transmit power
     3. Evaluate performance with infrequent ground tracking
     4. Best strategy for selection of receiveing antenna
     5. Sensibility analysis of RX to given uncertainty window
     6. Rest of cases evaluate performance of MGNSS RX covering all mission phases
  3. Main advantage of GNSS mostly visible during LTO
     1. High accuaracy of hybrid nav estimation
     2. Ground ops can be reduced to once per day
     3. Up to geo hybrid nav is significantly more precise than inertial nav, on-board orbit propagation and hourly ground track udate

1. Assisted GNSS Navigation in Lunar Missions
   1. <https://www.researchgate.net/profile/Giovanni_Palmerini/publication/269163714_Assisted_GNSS_Navigation_in_Lunar_Missions/links/550fe0230cf2ac2905af53c0.pdf>
   2. ***Moderate availability of weak signals with frequent outages***
   3. ***Software receivers able to capture signals***
      1. ***Computing nav message remains difficult task***
   4. ***Approach to obtain navigation solution is analyzed***
      1. ***Relevant requiements for clock and orbit propagator discussed***
   5. ***Potential to save operational costs related to ground support and tracking***
   6. Intensive processing using a software receiver can withstand low SNR
   7. Estimation techniques based on knowledge of the orbital dynamics solve issue of continuity
   8. Being that it is extremely difficult to get nav message from GNSS signals, ground station or a data-relay system can be used to upload a core portion of the navigation message
   9. Improvments could be made if Beidou and GLONASS are included
2. GNSS-based Orbital Filter for Earth Moon Transfer Orbits

* 1. <https://www.cambridge.org/core/journals/journal-of-navigation/article/gnss-based-orbital-filter-for-earth-moon-transfer-orbits/050B00CA697DD2339BEE061048DC0ADB>
  2. ***Adaptive orbital filter*** 
     1. ***Fuses GNSS observations with orbit forces model***
     2. ***Simulation results show accuracy significantly higher than with standalone GNSS or pure orbital propagation***
  3. Orbital filter specifically designed for MTO
     1. Fuses GNSS observations(Range and Rate) with an orbital forces model through and adaptive EKF
  4. Once Spacecraft goes above constellation, higher GDOP and weak signal degrade accuracy
     1. With no filtering errors of 10’s of Km and peaks higher than 50Km are seen at moon altitude(with Rx capable of signals down to -159dBm
  5. peaks of errors reduced with filter to about 260m (L1 C/A used for least square estimation) 10’s of cm/sec error for velocity
  6. Pos and vel estimation help estimate Doppler shift and rate
  7. Signifcant improvments when using both galileo and GPS

1. Navigator GPS Receiver for fast acquisition and weak signal space applications
   1. <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080040692.pdf>
2. A GPS Receiver for Lunar Missions(ION)
   1. <https://www.ion.org/publications/abstract.cfm?articleID=7685>
   2. ***Reduce reliance on DSN***
   3. ***“Navigator”*** 
      1. ***Developed at GSFC***
      2. ***At its heart is a Field programmable gate array(FPGA) based acquisition engine***
         1. ***Rapid acquisition/reacquisition of strong gps signals after outage***
         2. ***Lower sensitivity, allowing acquisition high above gps constellation***
      3. ***Asses Navigator at earth ascent, cislunar navigation, and entry***
      4. ***Navigator connected to Spirent GPS signal generator to allow for collection of real-time, hardware in loop results for each phase of flight***
      5. ***Navigator assessed under dynamical environment unique to mission phase trajectory***
3. GNSS-Based Navigation for Lunar Missions(ION)
   1. <https://www.ion.org/publications/abstract.cfm?articleID=12471>
   2. ***Overview of tools/methodology used in LunarGNSS project***
   3. ***Final results of LunarGNSS study***
      1. ***Expected environment characteristics***
      2. ***GNSS based nav performance achievable with proposed nav system architecture***
4. Weak GNSS Signal Navigation for Lunar Exploration Missions(ION)
   1. <https://www.ion.org/publications/abstract.cfm?articleID=12876>
   2. ***Carrier to noise ratio levels as low as 10 to 15 dBHz***
   3. ***Investigate mission phases***
      1. ***Transfer orbit***
      2. ***LLO***
      3. ***Lunar ascent/descent***
      4. ***Surface operations***
      5. ***Nav at L1&L2***
   4. ***Suggest GNSS receiver architecture***
      1. ***Snapshot receiver w/ limited ground station aiding to help with/substitute info from nav message***
      2. ***Integration with other sensors required for ascent/descent and LLO (INS and Radar altimeter)***
   5. ***Build off of on-board navigation propagator, includes kinematic model during outages***
   6. ***Mission date has slight effect on performance***
   7. ***Single steerable high gain antenna considered baseline for study***
   8. ***Developed snapshot receiver sim in matlab***
      1. ***Start with GPS L1 C/A signal then data-less pilot signals of Galileo E1 C and Galileo E5-Q/b-Q services***
   9. ***Suggested receiver concept relies on ground station aide or update from INS***
   10. ***Important for low-thrust missions***
5. Orbital Filter Aiding of a High Sensitivity GPS Receiver for Lunar Missions(ION)
   1. <https://www.ion.org/publications/abstract.cfm?articleID=13422>
   2. ***Adaptive orbital filter to aid GNSS acquisition/tracking***
   3. ***Describes orbit filter architecture***
   4. ***Tested with sprient GSS 8000 full constellation simulator for a highly elliptical MTO***